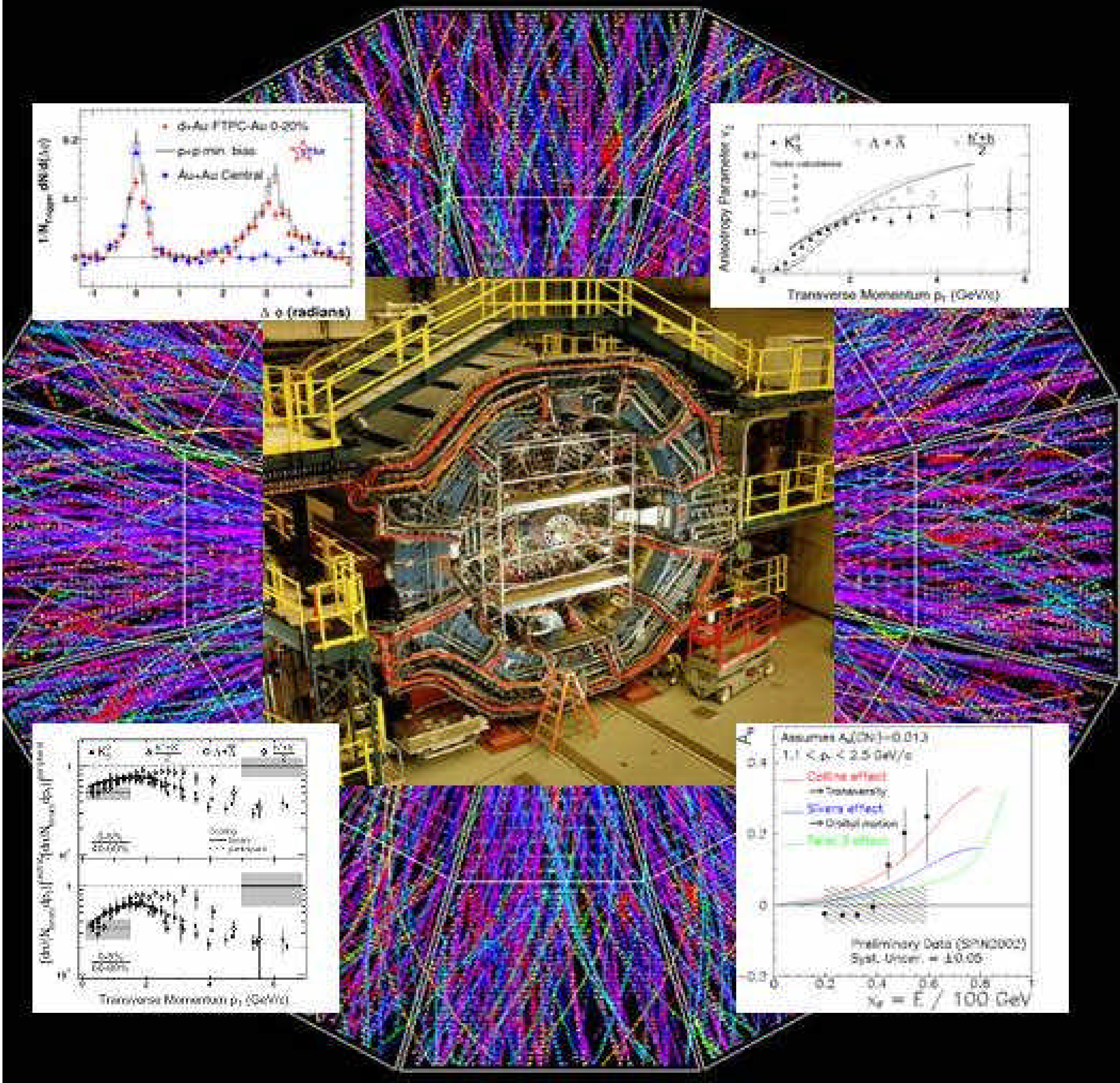
STAR Decadal Plan

The STAR Collaboration September, 2003



The STAR Decadal Plan: Executive Summary

In the coming decade, the STAR Collaboration envisions a world-leading program of focused studies to fully elucidate the fundamental properties of the new state of strongly interacting matter produced in RHIC collisions. These measurements will decisively establish the relation of this matter to the quark-gluon plasma state predicted to result from heating the QCD vacuum. They will further allow STAR to test and extend QCD theory and its predictions regarding the behavior of bulk color-deconfined matter.

Studies key to this program will include:

- measurement of the gluon density of the plasma using direct-photon tagged jets
- measurement of flavor tagged jets to test perturbative QCD predictions of the quark mass dependence of partonic energy loss
- measurement of spectra and yields for the Upsilon family of states to place significant constraints on the temperature in the initial stage of the collisions
- studying partonic collectivity by measuring bulk physics properties (e.g. spectra, elliptic flow, particle ratios, non-identical particle correlations) for particles and resonances containing light, strange, and charmed quarks
- detailed unfolding of large and small scale fluctuations and correlations for identified particles to map the dynamics and evolution of the produced matter
- studying the effects of chiral symmetry restoration via leptonic decays of hadronic resonances in-medium
- direct photon spectra via gamma-gamma HBT to provide information on the temperature and lifetime of the early time partonic and later stage hadronic phases using a penetrating probe

Additional studies will focus on the search for new phenomena in bulk QCD matter such as strong CP violation. Proton-nucleus studies to measure gluon densities at low momentum fraction to probe the effect of the nuclear medium on parton densities and determine initial conditions for nucleus-nucleus collisions will also be performed.

A focused program of spin physics measurements to study the spin structure of the proton will be carried out. The contribution to the proton spin from gluons will be determined using direct photon + jet, inclusive jets and di-jet production at moderately high p_T (>5 GeV/c). The flavor-dependence ($\bar{u}$ vs. $\bar{d}$) of the sea quark polarization, and thereby the mechanism for producing the sea in a proton, will be probed using parity-violating W production and decay. Additional studies of the effects of quark mass terms in the QCD Lagrangian and of quark transverse spin preferences in a transversely polarized proton will be carried out by measuring transverse spin asymmetries for b-quark jets, for π^o from forward-going jets, and for quark-quark di-jets.

To accomplish this program, the STAR detector will require significant upgrading. In the years up to 2010, when a factor of 4 increase over present heavy-ion collision luminosities is envisioned, the required upgrades include:

- a full acceptance TOF barrel based on multi-gap resistive plate chamber technology to significantly extend the momentum range of STAR's particle identification capabilities
- a precision micro-vertex detector capable of directly observing charm and beauty decays
- a high rate data acquisition system and corresponding TPC front end electronics upgrades to allow maximal utilization of RHIC luminosity to study bulk physics properties of the produced matter
- a forward tracking upgrade to enable reliable charge sign determination for W decay.

To accomplish these upgrade goals on the timescale demanded by the urgency of the physics questions, a robust program of detector R&D needs to begin now. A three year R&D program to accomplish the necessary technological advances was presented and approved by the Brookhaven Detector Advisory Committee in December 2002. The scope of the proposed plan is approximately $4M.

The above upgrades will be implemented through evolutionary modification of the STAR Detector to significantly extend STAR's scientific reach during the ongoing program. They encompass a scope of approximately $20M which is envisioned to be funded as much as possible within the existing base. The STAR spin physics program ongoing during this period will require successful completion of the RHIC development program to achieve design luminosity and beam polarization by 2006 (an increase from current performance of a factor of ~20 to of order 10-20 pb^{-1}/week and ~2 to ~ 70% respectively).

The most statistics-challenged measurements planned in the next decade for AuAu collisions (e.g. high p_T photon and flavor tagged jets) require an additional increase of a factor of 10 in RHIC luminosity. This capability will be achieved near the end of the present decade by electron cooling of the ion beams accomplished as part of the RHIC II construction project. On this same timescale a new, compact fast TPC incorporating GEM readout will be installed in STAR. This device will be capable of robust operation in a high luminosity (40 x present performance) environment. It will extend STAR's capability dramatically, providing the performance required for seminal direct-photon HBT measurements and high p_T tagged jet studies. The cost of constructing the new STAR TPC is envisioned to be included in the cost of the RHIC II construction project.

1 The STAR Decadal Plan: Introduction

The decadal plan presented in this report has been developed by the STAR Collaboration in response to a letter from the Associate Laboratory Director for High Energy and Nuclear Physics of Brookhaven National Laboratory, Dr. Thomas B. W. Kirk. In his letter of February 28, 2003 (Appendix 1), Dr. Kirk charged STAR with preparing a document to communicate its vision of the compelling science to be carried out with the STAR Detector in the coming decade. The information contained in this document is intended to provide a snapshot of the status of the ongoing STAR scientific program, expected progress in the next several years, and compelling science that can be addressed with an upgraded STAR Detector in the RHIC II era. The essential upgrades required to accomplish the planned physics program are also discussed.

The first three runs at RHIC have allowed STAR to accumulate a wealth of data from p+p, d + Au, and Au + Au collisions on event-by-event observables, inclusive spectra for strange, non-strange, and charmed mesons, baryons, and resonances, and the spectra of leading hadrons from hard-scattered partons. These results have led quickly to the discovery of qualitatively new behavior, not previously observed, indicating the formation of a strongly interacting dissipative medium in central Au + Au collisions at RHIC. This discovery, observed by the other RHIC experiments as well, has been published in Physical Review Letters (Phys. Rev. Lett. 91 072304 (2003)) and reported to the scientific community at a special joint colloquium at Brookhaven National Laboratory on June 18, 2003 attended by the Presidential Science Advisor, Dr. John Marburger.

The primary goal of the STAR heavy ion program in the next several years will be to determine whether these results indicate a new phase of matter with bulk properties which are partonic has been discovered. Key questions that remain to be answered include whether the observed dissipation and collective behavior occur at the partonic stage, and whether a phase transition to a system which is deconfined and thermalized has taken place. Beyond this initial "discovery phase" the STAR research program will turn to a broader and deeper exploration of the fundamental properties of matter created by heating the QCD vacuum, and to testing and extending QCD theory and its predictions regarding the behavior of bulk color-deconfined matter. Direct photon and flavor tagged jets will be used to test perturbative QCD predictions of the quark mass dependence of partonic energy loss. Partonic collectivity will be studied by measuring bulk physics properties (e.g. spectra, elliptic flow, particle ratios, non-identical particle correlations) for particles and resonances containing light, strange, and charmed quarks. The measurement of spectra and yields for the Upsilon family of states will place significant constraints on the temperature in the initial stage of the collision.

The first polarized proton runs at RHIC using beams of transversely polarized protons have led to important new results from STAR indicating a large analyzing power for the single spin asymmetry of neutral pions produced at large Feynman x and moderate p_t. In the coming decade, it is envisioned that a broad spectrum of world class spin physics studies will be carried out. The contribution to the proton spin from gluons will be determined using direct photon + jet, inclusive jets and di-jet production at moderately high p_T (>5 GeV/c). The flavor-dependence (ubar vs. dbar) of the sea quark polarization, and thereby the mechanism for producing the sea in a proton, will be probed using parity-violating W production and decay. Additional studies of the effects of quark mass terms in the QCD Lagrangian and of quark transverse spin preferences in a transversely polarized proton will be accomplished by measuring transverse spin asymmetries for b-quark jets, for π^o from forward-going jets, and for quark-quark di-jets. To carry out this program will require successful completion of the RHIC development program to achieve design luminosity and beam polarization by 2006 (an increase from current performance of a factor of ~20 to of order 10-20 pb^{-1}/week and ~2 to ~ 70% respectively).

The scientific directions above comprise the main thrust of the future scientific program envisioned by STAR. The large acceptance and excellent tracking capability of the STAR detector result in considerable flexibility for other important scientific measurements and those are also discussed as part of the proposed 10 year plan.

To accomplish the scientific program planned for the coming decade, the STAR detector requires significant upgrades. In the past several years, a number of workshops have been held to discuss the evolution of the detector necessary to carry out this program. These discussions have indicated that the physics goals of the high-luminosity STAR program will be most effectively achieved through evolutionary upgrades to the existing STAR detector, maintaining a strong physics program through the remainder of this decade with new components being phased in during the annual shut-downs. This approach will significantly extend the physics reach of STAR in order to take full advantage of the $4 \times L_0$ phase and will enable STAR to be fully capable of exploiting the full luminosity upgrade ($40 \times L_0$) when the machine improvements for the RHIC II program are completed.

These upgrades include:

- a full acceptance TOF barrel based on multi-gap resistive plate chamber technology to significantly extend the momentum range of STAR's particle identification capabilities
- a precision micro-vertex detector capable of directly observing charm and beauty decays
- a high rate data acquisition system and corresponding TPC front end electronics upgrades to allow maximal utilization of RHIC luminosity to study bulk physics properties of the produced matter
- a forward tracking upgrade to enable reliable charge sign determination for W decay
- a new, compact fast TPC incorporating GEM readout capable of robust operation in a high luminosity (40 x present performance) environment to provide the performance required for seminal direct-photon HBT measurements and high pt tagged jet studies.

Instrumenting the forward STAR acceptance with hadron calorimetry and roman pots to extend STAR's scientific reach for spin physics and diffractive physics measurements is also being considered.

To accomplish the necessary upgrades on the timescale demanded by the urgency of the physics questions, a robust program of detector R&D needs to begin now. A three year R&D program to accomplish the necessary technological advances was presented and approved by the Brookhaven Detector Advisory Committee in December 2002. The scope of the proposed plan is approximately $4M. The overall strategy is to accomplish a series of incremental upgrades of the STAR detector's capabilities between now and 2010 within the existing base program as much as possible. Upgrade construction not possible within the base budget would be included in the cost for the RHIC II construction project.

This program will be carried out by the members and institutions of the STAR Collaboration. During the coming ten year period it is expected that some STAR institutions will naturally shift priority to participation in the heavy ion program at the Large Hadron Collider due to various considerations, and that toward the end of this period some will naturally have an increasing focus on spin studies at e-RHIC. However, the number of institutions joining STAR with a long-term focus on the STAR physics program is steadily growing. Overall, it is expected in the coming decade, that despite some dynamic change in the make-up of the institutions with a primary focus on STAR/RHIC, a strong STAR Collaboration with the necessary level of interest, vitality, and staying power will be maintained due to the attractiveness of the science that can be accomplished and the fact that RHIC is a dedicated facility.

With respect to the proposed heavy ion program, an important consideration will be the nature of particle production at higher energy in an eventual heavy ion program at the LHC. This will likely be much more sensitive to the low Bjorken-x behavior of the parton distribution functions and may well be fundamentally different than that produced at RHIC. The high-luminosity, heavy ion studies envisioned in the STAR Decadal Plan are focused on fully characterizing the QCD matter expected to be produced *at RHIC*. As a practical matter, the type of measurements planned for the high luminosity physics program at RHIC will not begin at the LHC until well after the initial survey phase of that program which is scheduled to begin near the end of the present decade. These measurements require large data samples, taken over long running periods with multiple beam conditions. The necessity of detailed cross-comparisons of p+p, p(d)+ A, and A+A results has been clearly demonstrated in the first runs at RHIC. The continuing availability of all three collision programs will be a key strength of the RHIC program throughout the LHC era. A detailed understanding from the RHIC program may well be required to help guide the LHC experiments to those measurements where the high energy may be exploited to best advantage, given the limited heavy ion running time (~1 month per year) planned to be made available by CERN.

The sections which follow discuss the scientific accomplishments achieved by STAR in the first RHIC runs, expected progress with the existing detector from 2004-2006, and the compelling physics the STAR Collaboration expects to accomplish with an upgraded STAR Detector in the next ten years (Section 2). The upgrades key to carrying out the proposed program are discussed in Section 3. Collectively, the discussions in this report serve as a beginning roadmap for the future physics program of STAR. Future updates and refinements to this document will be made to reflect new knowledge resulting from ongoing simulations and data analyses, and to address funding priorities and timelines as STAR prepares for the construction of the upgrades needed to carry out this program. An important need in progressing towards the RHIC II era and establishing scientific funding priorities will be significant theoretical advances to leverage new knowledge resulting from ongoing data analyses and simulations.

1.1 The STAR Relativistic Heavy Ion Physics Program: Accomplishments and Expected Progress in 2004-2006

During the first three RHIC runs, the large acceptance tracking coverage and excellent momentum resolution of the STAR detector has enabled the STAR Collaboration to perform an extensive initial survey of the matter produced in relativistic p+p, d+Au, and Au+Au collisions, including event-by-event measurement of global observables, inclusive spectra for strange, non-strange, and charmed mesons, baryons, and resonances, and the measurement of leading hadrons from hard scattered partons. These studies have focused on investigating strongly interacting matter at high energy density and the search for the quark-gluon plasma. They have quickly led to the discovery of qualitatively new behavior, not previously observed, which indicates the creation of a dense, dissipative medium which is strongly interacting, and exhibits strong pressure gradients and collective behavior in the early stage of the collision.

Comparison of inclusive yields of high pt charged particles and the correlation of back-to-back leading charged hadrons has shown[1,2,3,4,5] (Figure 1) that inclusive high p_t particle production and "away side" leading hadrons are strongly suppressed in central Au+Au collisions relative to the yields in p+p, peripheral Au+Au, and central d+Au collisions. These studies show that the strong suppression (a factor of 5) observed in central Au+Au collisions is due to final state interactions in a dense, dissipative medium produced during the collision and not to the initial state wave function of the Au nucleus. The picture which emerges is that energetic partons traversing the medium produced in head-on Au+Au collisions lose sufficient energy that only those streaming outward from near the surface of the system produce the jets observed.

Measurement of the elliptic flow, v_2 (the second fourier coefficient of the azimuthal anisotropy of the transverse momentum distribution), for a wide range of strange and non-strange mesons, baryons, and resonances[6,7,8] (Figure 2-Figure **3**) has shown that the early stage of the collision is characterized by the buildup of large pressure gradients, and that the matter is strongly interacting and exhibits collective behavior during this stage. Elliptic flow measured for identified particles as a function of p_t has shown potential sensitivity to the underlying equation of state, with the distribution measured for protons being best described by a model dependent equation of state for matter with partonic degrees of freedom[9,10] (Figure 3). The behavior of v_2 as a function of p_t above ~ 2 GeV/c supports the conclusion that a dense, dissipative medium has been formed, the magnitude of the elliptic flow saturating[4] (Figure 4) and staying constant out to transverse momenta (~ 6 GeV/c) where fragmentation from jets is expected to dominate.

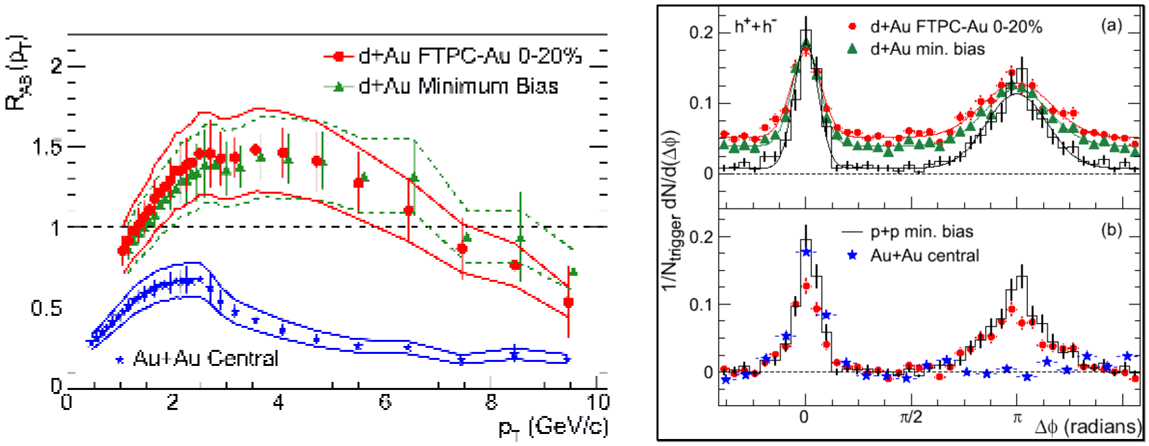


Figure 1. Left panel: Charged hadron nuclear modification factor for minimum bias and central d+Au collisions, and central Au+Au collisions. Minimum bias data are displaced 100 MeV/c to the right for clarity. There is a strong suppression (a factor or 5) of leading hadrons relative to the yields in p+p, peripheral Au+Au, and central d+Au collisions. Right panel: a) Efficiency corrected two-particle azimuthal distributions for minimum bias and central d+Au collisions and for pp collisions. The curves used to fit the data are explained in [1]. b) Comparison of two-particle azimuthal distributions for central d+Au collisions to those seen in p+p and Au+Au collisions. The respective pedestals have been subtracted.

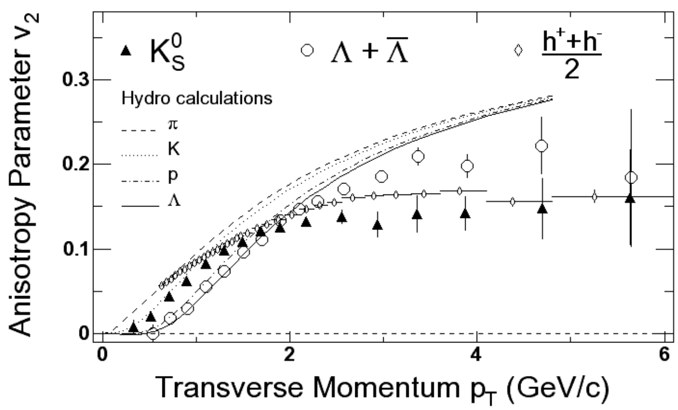


Figure 2. The minimum bias (0-80% of the collision cross section) $v_2(p_T)$ for K^0_S, $\Lambda + \overline{\Lambda}$, and $h^{\pm}$. Error bars shown are statistical. Hydrodynamic calculations for pions, kaons, protons, and lambdas are discussed in [6].

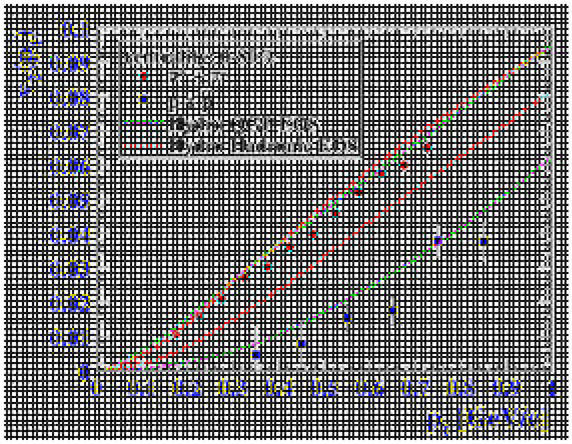


Figure 3 $v_2(p_T)$ for pions and protons at $\sqrt{s}$ = 130 GeV. The lines are hydrodynamic calculations for several presumed equations of state. For protons (closed squares) the best agreement is for an equation of state which assumes quark-gluon plasma formation (from [11]).

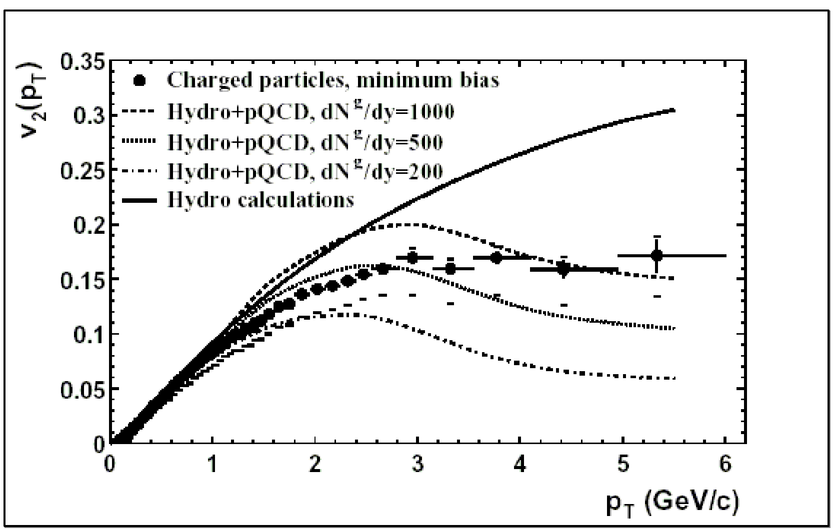


Figure 4. $v_2(p_T)$ for minimum-bias events (circles). The error bars represent the statistical errors and the caps show the systematic uncertainty. At ~ 2 GeV/c, the magnitude of v_2 saturates. Above 2 GeV/c it remains approximately constant out to the high end of the measured p_t range. The data are compared with hydro + pQCD calculations assuming the initial gluon density used as input for the pQCD calculation is dNg/dy = 1000 (dashed line), 500 (dotted line), and 200 (dashed-dotted line). A pure hydrodynamical calculation (solid line) is also shown (from [4]).

Further evidence supporting a picture in which the early stage of the collisions is characterized by the buildup of strong pressure gradients and collective behavior in an asymmetric region of overlap is provided by azimuthally sensitive Hanbury-Brown Twiss interfometry. The results show clearly that second order oscillations typical of an out-of-plane extended source characterize azimuthal two-particle correlations observed in the final state[12] (Figure 5). The evolution of the overlap region is apparently sufficiently fast that the expansion of the system does not have time to quench the strong pressure gradients leading to elliptic flow. The mass dependence of particle spectra, combined with other HBT measurements show there is strong radial flow. The effect of radial flow appears to differ for multiply strange baryons (Ξ, Ω) compared to lighter particles (π, K, p)[13] (Figure 6), possibly providing access to information on collectivity in the early partonic stage.

Extensive measurements of spectra for strange and non-strange mesons and baryons have shown that the intermediate p_t region (2-6 GeV/c)[6] (Figure 7) is complex, and that collision dynamics play a significant role in the transition from the soft to hard scattering regimes. Measurement of the complete spectrum of strange particles[14] (Figure 8) as well as a broad range of short-lived hadronic resonances[15] (Figure 9, Figure 10) (many observed for the first time in relativistic heavy ion collisions) has provided the means for a detailed study of the late-stage chemical and thermal evolution of the system.

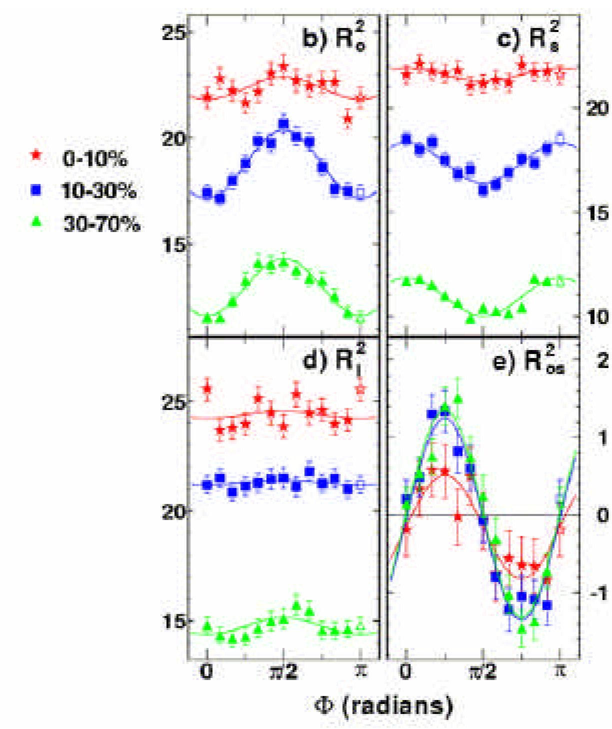


Figure 5. Azimuthally sensitive HBT radii as a function of centrality. Second-order oscillations are observed which indicate the source for particle emission is out-of-plane extended (from [12]).

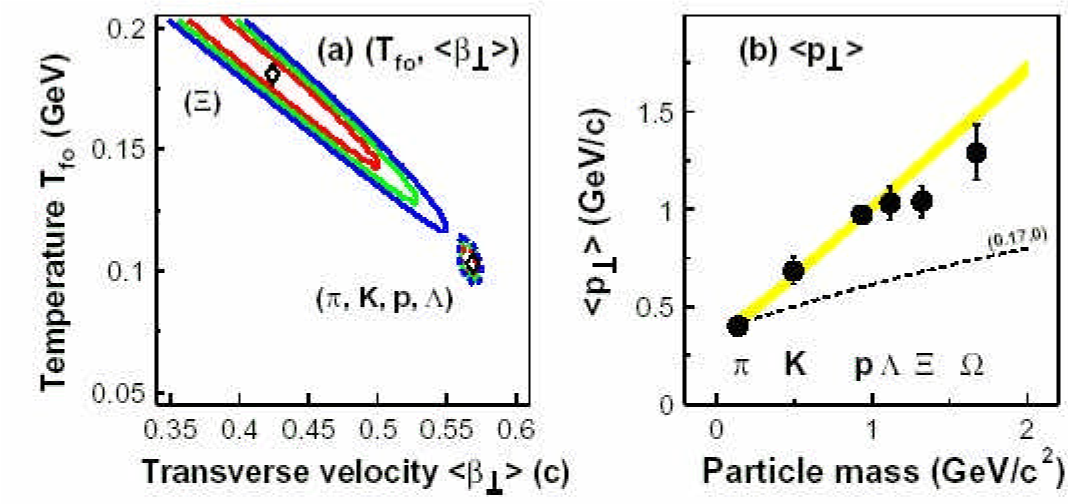


Figure 6. a) The kinetic freeze-out temperature versus transverse flow velocity for hydrodynamically inspired model fits to $m_\perp$ spectra. Contours are shown for 1, 2, and 3 standard deviations. Solid curves are for a simultaneous fit to the Ξ^- and $\overline{\Xi}^+$. Dashed curves are a separate fit to STAR π, K, p, and Λ data. The diamonds are the best fit in both cases. b) Mean transverse momentum for identified particles versus particle mass. The band results from a 3 sigma contour to the hydro model fit to the π, K, p, and Λ data, and the dashed curve is for T_{fo} = 170 MeV, and $<\beta_\perp>$ = 0. (from ref. 13)

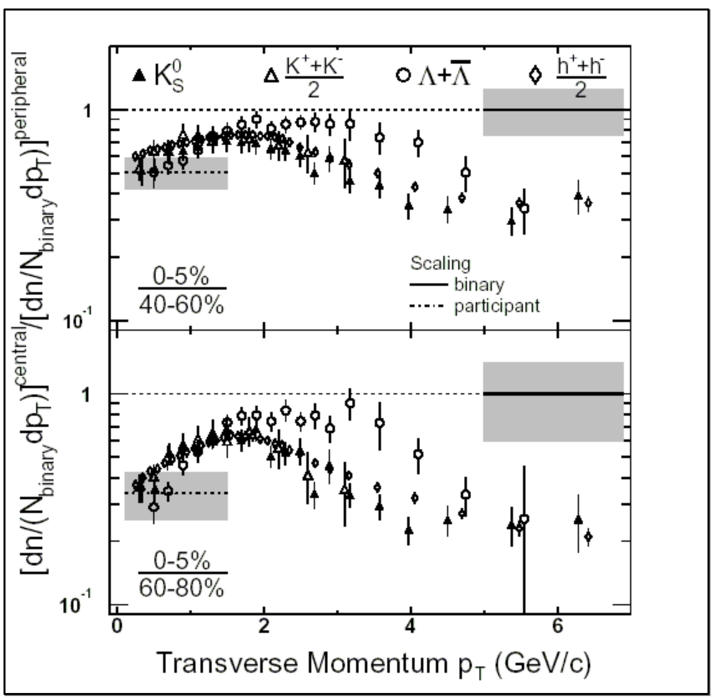


Figure 7. R_{CP} for K^o_s, $K^\pm$, and $\Lambda + \overline{\Lambda}$ at mid-rapidity calculated using centrality intervals, 0–5% vs. 40–60% (top) and 0–5% vs. 60–80% of the collision cross section (bottom). The error bars shown on the points include both statistical and systematic errors. The widths of the gray bands represent the uncertainties in the model calculations of N_{binary} and N_{part}. Also shown is the charged hadron R_{CP} measured by STAR for $\sqrt{s_{NN}}$ = 200 GeV (from [6]).

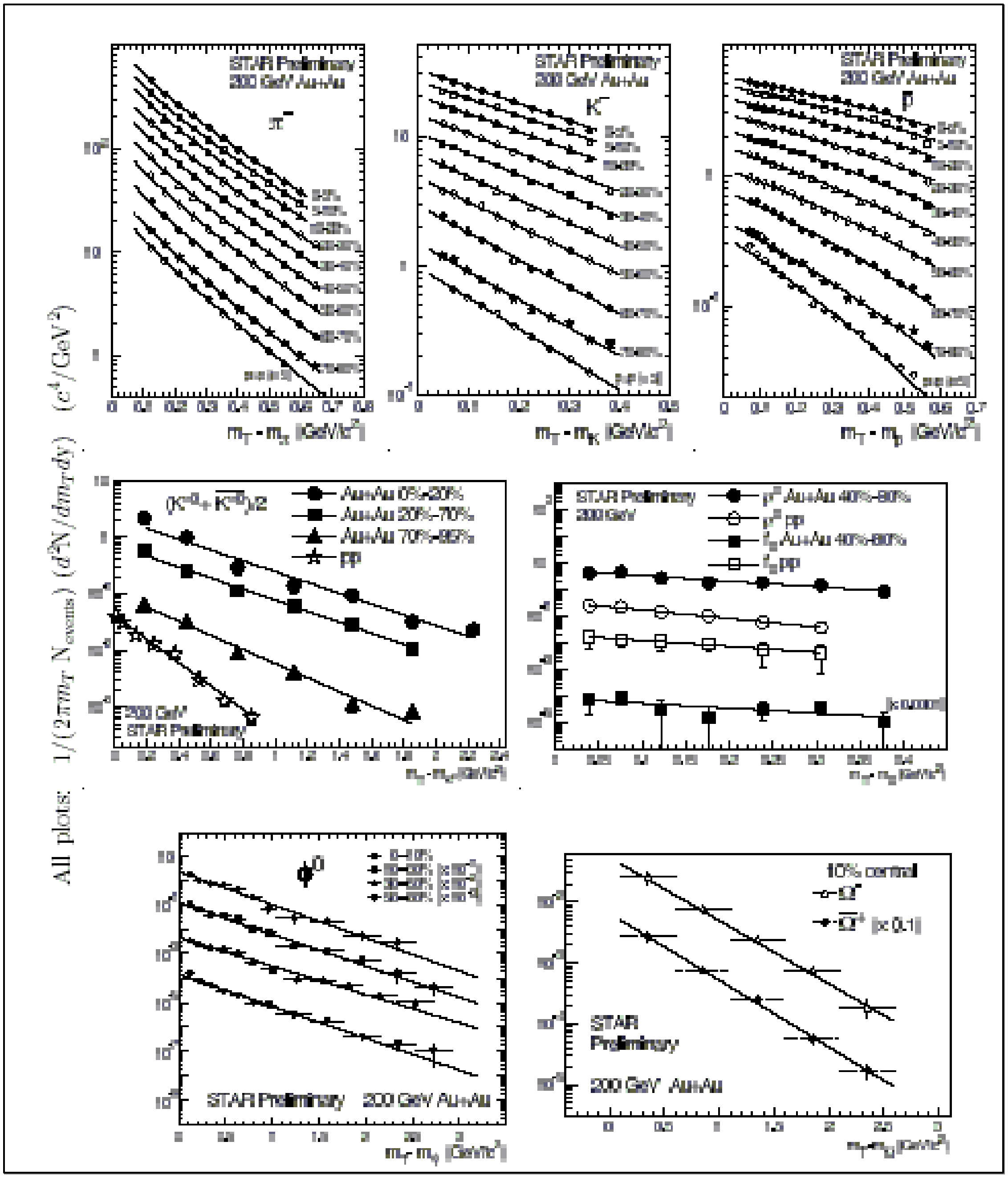


Figure 8. A selected sample of STAR data demonstrating the diversity of spectra available for developing a detailed picture of the evolution of the hadronic stage between chemical and kinetic freeze-out (from [14]).

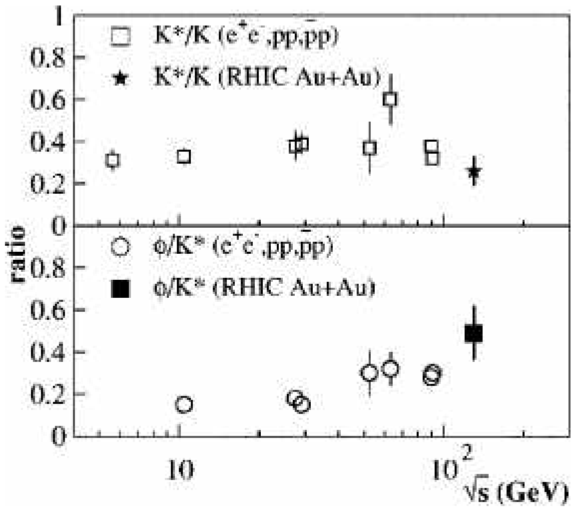


Figure 9. Particle ratios that can be used to unfold the dynamics of the late stage evolution of the collision. The K^{*o} to charged kaon and ϕ to K^{*o} ratios for different colliding systems as a function of $\sqrt{s}$. Data are shown with quadratically combined systematical and statistical errors. The data are from collisions of e^+e^- at $\sqrt{s}$ of 10.45 GeV, 29 GeV, and 91 GeV, $\bar{p}$-p at 5.6 GeV, and pp from the ISR at 63 and 52.5 GeV and NA27at 28 GeV. Ratios shown are for total integrated yields except for the present measurements ($|y| < 0.5$) and those from the ISR at $\sqrt{s}$ = 63 GeV where the ratio is for midrapidity (from ref. [15]).

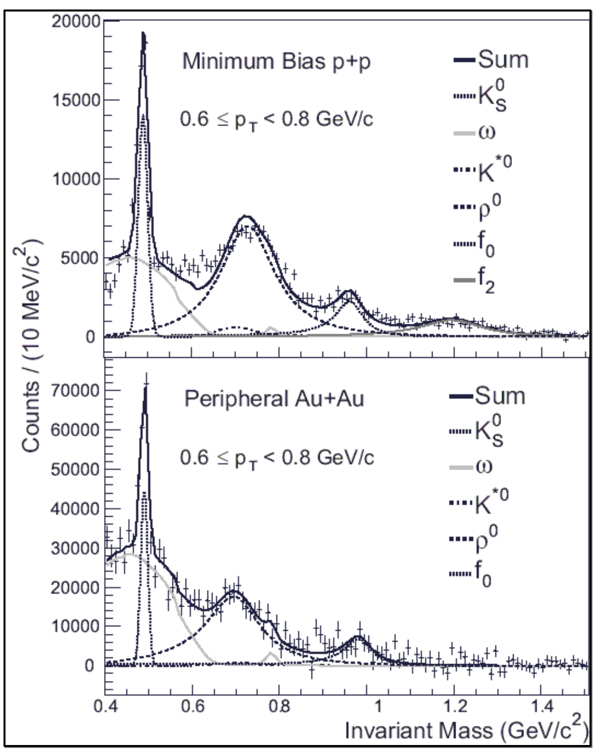


Figure 10. The raw $\pi^+\pi^-$ invariant mass distributions after subtraction of the like-sign reference distribution for minimum bias p+p (top) and peripheral Au+Au (bottom) interactions (from ref. [16]).

The first large-acceptance measurement of $< p_t >$ fluctuations at RHIC by STAR[17] **(**Figure 11) has revealed intriguing deviations from a central limit statistical reference. A striking 17 ± 2%

(stat+syst) *rms* excess of charge-independent fluctuations is observed in $\sqrt{n}\,(<p_t> - \hat{p}_t)/s_{\hat{p}_t}$ (extrapolated to 100% of primary charged particles in the acceptance for the 15% most-central events), possibly indicating hierarchical p_t production —initial-state scattering followed by parton cascade— in the early stage of the collision which is not fully equilibrated prior to kinetic decoupling.

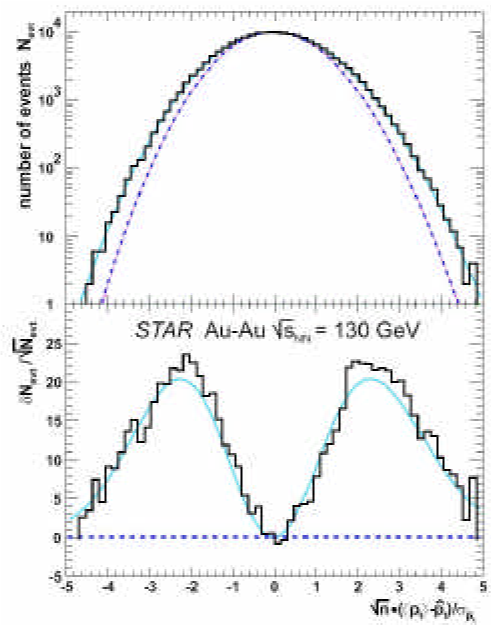


Figure 11 Upper panel: Event-number distribution on $\sqrt{n}(\langle p_T\rangle - \hat{p}_T)/s_{p_T}$ for 80% of primary charged hadrons in |η|<1 for 183k central events (histogram) compared to CLT gamma reference (dashed curve). Monte Carlo CLT reference (solid curve underlying gamma reference) and broadened gamma distribution (solid curve underlying data)[18]. Lower panel: difference in upper panel between data and gamma reference (histogram) or between broadened gamma and gamma reference (solid curve) divided by Poisson error.

These and other results from the initial survey performed by STAR have shown that the matter being produced exhibits features qualitatively different from those observed before in collisions of heavy nuclei. The following picture emerges.

The system is highly dynamic and the evolution is fast; characteristic features include:

- Transverse expansion with an average velocity of ~ 0.55 c
- A large degree of anisotropic flow (v_2) suggesting hydrodynamic expansion and high pressure at early times in the collision history
- The duration of hadronic particle emission appears to be very short
- Near side correlations show that the fragmentation properties of the observed jets are the same in p-p collisions and all centralities for Au-Au collisions indicating that the fragmentation in Au-Au collisions occurs in vacuum

The produced matter is opaque, exhibiting:

- Persistence of the saturation of v_2 at high p_T
- Suppression of high p_T particle yields relative to binary scaled p-p
- Suppression of away side leading particles from jets

- Large-scale correlations of net charge, total charge, and $< p_t >$

Statistical models describe the final state well as indicated by:

- Excellent fits to particle ratio data with equilibrium thermal models
- Excellent fits to flow data with hydrodynamic models that assume equilibrated Systems
- Chemical freeze-out at about 175 MeV; thermal freeze-out at about 100 MeV

The question of whether or not a new phase of matter is being produced with bulk properties which are partonic is yet to be answered. It remains to be shown that the dissipation and collective behavior occur at the partonic stage, that the system is deconfined and thermalized, and that a phase transition has occurred.

The primary goal of the STAR scientific program from 2004-2006 will be to answer these questions definitively using the full capability of the existing STAR detector, including the baseline detectors (Time Projection Chamber, DAQ, Trigger, and Magnet), detectors funded through the Additional Experimental Equipment initiative (Barrel Electromagnetic Calorimeter and Silicon Vertex Tracker), and other essential detectors provided by additional major investments: the Endcap Electromagnetic Calorimeter (NSF), Forward Time Projection Chambers (MPI), Silicon Strip Detector (IN2P3), and Photon Multiplicity Detector (VECC) . Prototype detectors for an eventual Time of Flight Barrel based on multi-gap resistive plate chamber technology will also be commissioned by scientists from the United States and China.

Using this suite of detectors STAR will complete its initial survey of soft physics observables (spectra, strangeness, event-by-event fluctuations and correlations, etc.) and extend its measurement of elliptic flow to the heaviest multiply strange baryons. Exploratory studies will be performed to establish the yields of open charm, charmonium, and bottomonium and to set the stage for future studies of possible charm quark thermalization and color screening of heavy quark bound states. In addition, the feasibility of using kinematic selection of the parton-parton center of mass for di-jet events and the measurement of high transverse momentum D mesons to isolate the jet fragmentation resulting from light quarks, gluons, and heavy quarks will be studied. These partons are expected to couple differently to dense partonic matter and observation of differential energy loss for these probes would provide important information on the nature of the medium that has been produced. A key requirement for making strong progress during this period will be increased insight and guidance from nuclear theory, particularly concerning the range of phenomena possible from hadronic scenarios.

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1.2 Overview of the STAR Scientific Program in the RHIC II Era

Beginning during the second half of this decade, the STAR research program will turn to a broader and deeper exploration of the fundamental properties of matter created by heating the QCD vacuum, the accompanying phase transitions, and the extremely hot, superdense states that precede the formation of a thermal plasma of quarks and gluons. These studies will address e.g., the nature of chiral symmetry breaking and how is it related to the masses of the hadrons; the relationship between the deconfinement and chiral transitions; the nature of a possible saturated gluon state in strongly interacting particles. The new matter produced at RHIC will provide a unique laboratory for a full, detailed exploration of the fundamental properties of QCD. Extensive studies of proton-nucleus and polarized proton collisions will provide essential information on the initial conditions, and the role of spin as a fundamental component of QCD.

The STAR physics program during the high luminosity era will center on precision measurements e.g., of the dynamics of heavy flavor (charm and beauty) production as a means of studying the various stages of formation and hadronization of QCD matter, detailed measurements of observables related to hard-scattering of partons in the kinematic range where perturbative QCD calculations can be reliably carried out, use of electromagnetic probes (including direct photons) to study the formation and evolution of a deconfined state, and extended capability for the study of new effects related to the spin structure of the nucleon with the RHIC Spin program.

Studies key to fully characterizing the properties of the quark-gluon plasma, and the QCD vacuum will include:

- measurement of the gluon density of the plasma using direct-photon tagged jets
- measurement of flavor tagged jets to test perturbative QCD predictions of the quark mass dependence of partonic energy loss

- measurement of spectra and yields for the Upsilon family of states to place significant constraints on the temperature in the initial stage of the collisions
- detailed unfolding of large and small scale fluctuations and correlations for identified particles to map the dynamics and evolution of the produced matter
- studying partonic collectivity by measuring bulk physics properties (e.g. spectra, elliptic flow, particle ratios, non-identical particle correlations) for particles and resonances containing light, strange, and charmed quarks
- studying the effects of chiral symmetry restoration via leptonic decays of hadronic resonances in-medium
- direct photon spectra via gamma-gamma HBT to provide information on the temperature and lifetime of the early time partonic and later stage hadronic phases using a penetrating probe

Additional studies will focus on the search for new phenomena in bulk QCD matter such as strong CP violation which is expected to be associated with the deconfinement phase transition. Such studies require very large samples of unbiased data ($>10^8$ events).

1.3 The STAR Spin Physics Program: Status and Future Plan

A second major component of the STAR scientific program is focused studies of the spin structure of the proton, including the spin dependent gluon distribution $\Delta G(x)$, the polarization of the valence quarks and sea anti-quarks (Δu, Δd, $\Delta \bar{u}$, $\Delta \bar{d}$), and the transversity distribution (alignment of quark spins transverse to the direction of motion for a proton with transverse polarization), and possible parity violation beyond that expected from the standard model.

Although the STAR spin physics program is still in its infancy, the first polarized protons runs at RHIC have already yielded important new results. Specifically, the study of forward neutral pion production at large Feynman x and moderate p_t has indicated a large analyzing power for single spin asymmetries in collisions of transversely polarized protons[19] (Figure 12). These exciting results suggest a strong sensitivity to aspects of the parton distributions tied to the transverse spin orientation of a proton. That covers transversity and the so-called Sivers effect, which is a preference for quark transverse momentum in a proton to be directed to one side or the other of the plane formed by the spin direction and the proton's momentum direction. In addition to first physics results, significant progress has been made in constructing and deploying the hardware and infrastructure needed for the present and future STAR spin physics program. Spin-sorted scalers have been implemented, beam-beam counters which serve as local polarimeters have been constructed and commissioned, and six of eight eventual lead glass hodoscopes (top and bottom, left and right on both ends of the STAR detector) have been installed. In Run 3, an important accomplishment was the use of the beam-beam counters to commission the spin rotators on either side of the STAR intersection and demonstrate they could be tuned to provide longitudinal polarization at the STAR intersection. Progress in constructing the STAR Endcap

Electromagnetic Calorimeter to provide essential kinematic coverage for the study of $\Delta G(x)$ is ongoing.

The program planned for the future includes determining the contribution to the proton spin from gluons by measuring the two-spin asymmetry A_{LL} for direct γ + jet (QCD Comtpon) coincidences in collisions of longitudinally polarized protons. The flavor-dependence (ubar vs. dbar) of the sea quark polarization, and thereby the mechanism for producing the sea in a proton, will be probed using parity-violating W production and decay. Additional studies of the effects of quark mass terms in the QCD Lagrangian and of quark transverse spin preferences in a transversely polarized proton will be accomplished by measuring transverse spin asymmetries for b-quark jets, for pi-zeros from forward-going jets, and for quark-quark di-jets. High p_t di-jet production will be measured to search for unexpected sources of parity violation in quark-quark elastic scattering at very high p_t (~ 100 GeV/c).

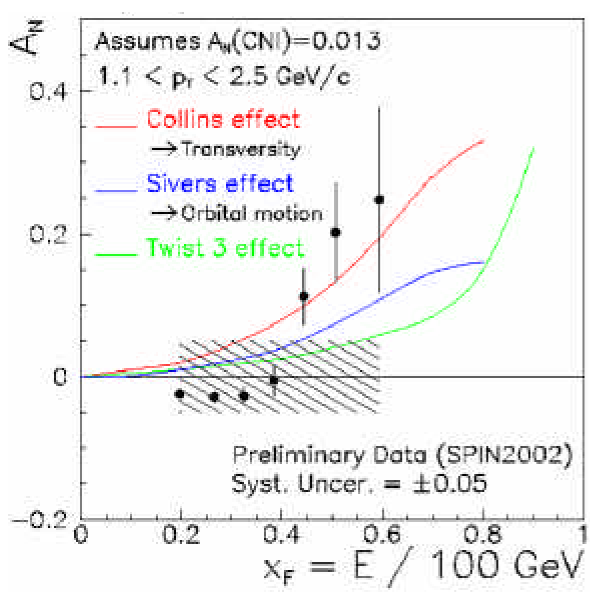

Figure 12. STAR results for the analyzing power for forward π^0 production at large pseudorapidity ($3.3 \leq \eta \leq 4.1$). The data are compared to several calculations including one based on the Collins effect, corresponding to a spin dependent fragmentation (red curve), on a twist-3 quark-gluon correlation responsible for the spin effect evaluated at p_T =1.5 GeV/c (green curve), and on the Sivers effect, where the spin effects arise from a correlation between the quark spin and its transverse momentum in the distribution function (blue curve) (from ref. [19]).

The main requirements for the STAR spin physics program up to 2006 are completion of the endcap and barrel electromagnetic calorimeters in 2004, completion of the AGS strong snake and gas-jet target in time for RHIC Run 5, and an increase of the RHIC luminosity for polarized protons by a factor of ~ 20 by 2006. A corresponding increase in polarization by a factor of ~ 2 is needed on the same time scale. In the longer term, a forward tracking upgrade will be required to provide efficient charge sign determination for studies of W decay in the years from 2006-2010. The addition of forward hadron calorimetry ($|\eta| > 2$) to reconstruct jets in association with forward π^o production is also being considered to study the Collins angle in forward jet production.

1.4 The STAR Ultra-Peripheral Collision Program

Ultra-peripheral collisions studies in the first heavy ion runs at RHIC have demonstrated the possibility for carrying out a unique program to study coherent particle production[20] (Figure 13).

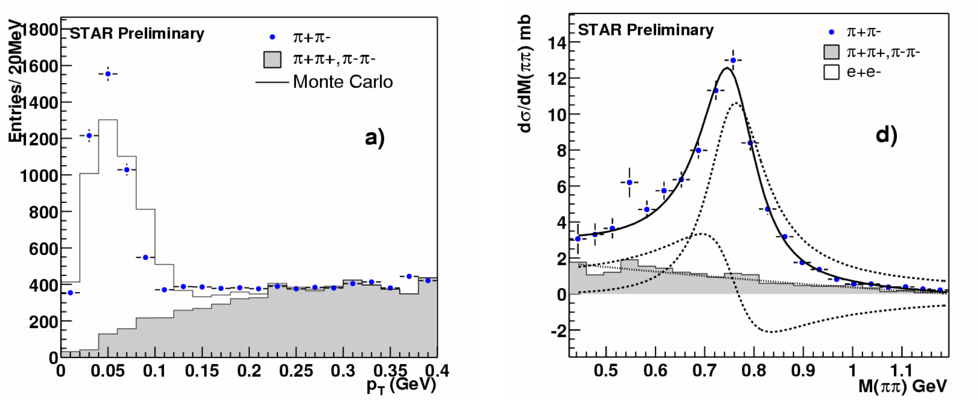

Figure 13. The p_T and π-π invariant mass spectrum of two-track events collected in 200 GeV Au-Au collisions with the minimum bias trigger, from coherent photoproduction of ρ^o and direct π-π pairs accompanied by mutual Coulomb excitation. The p_T spectrum is peaked below 100 MeV/c, as expected for a photon from the electromagnetic field of one nucleus scattering coherently from the other nucleus, emerging as a vector meson.

In the period up to 2006 and beyond, STAR will extend its seminal program of two-photon, photon-pomeron, and pomeron-pomeron studies, to more fully explore the quark spectroscopy underlying the structure of hadronic matter, and search for exotic states and interactions. Additionally these studies will provide important information of the initial-state parton distributions of the Au nucleus. They are fully complementary to the spin physics and quark-gluon plasma studies STAR will perform, representing another important source of information to help test and extend QCD theory and its predictions. Roman pots to extend this program to diffractive physics studies are being considered.

2 The STAR Ten Year Physics Plan

The major goal of STAR for the near-term future is to establish whether the dense, dissipative matter formed at RHIC is indeed partonic in nature. Anticipated steps on the path to this goal have been outlined in the introduction. In this section we discuss a longer-term program of measurements aimed at exploiting RHIC's unique opportunity to elucidate the properties of hot, dense, matter. The degree of thermalization of the matter, its early temperature and the presence of collective behavior of the partons will be probed by measurements of yields, spectra, and elliptic flow for heavy hadrons which do not contain up or down quarks or alternatively, contain at least one charm or bottom quark. Comparative measurements of jet and high p_T hadron suppression for heavy *vs*. light quarks will test QCD predictions of substantial differences in energy loss of these partons in traversing matter with high gluon density. RHIC II will provide an order of magnitude luminosity upgrade and will facilitate coincidence measurements with photons in nucleus-nucleus collisions, at both low (two-photon HBT) and high (γ-tagged jets) p_T, thereby allowing a quantitative study of the properties of the early partonic matter, without the complications from the interactions of hadrons on their way out from the collision zone. All of these measurements require the acquisition of large data samples with an upgraded STAR detector. This longer-term program will be crucial to fully characterize the new form of matter produced at RHIC and to verify in all respects, that it demonstrates the properties predicted for the Quark Gluon Plasma. In addition to measurements of bulk properties of this fleeting matter, we will begin to probe the degree to which fundamental symmetries are either broken (e.g., CP-invariance) or restored (chiral and $U_A(1)$ symmetry). The possibility of tracing the change in symmetry conditions as matter enters a new phase represents an extraordinary opportunity for RHIC.

To interpret our measurements in terms of properties of partonic matter, we must also understand the nature of both the initial state nuclei (*e.g.*, gluon density) and the late stage hadronic medium and their effects on our measurements. Methods of approach to these studies are outlined below for both nucleus-nucleus and proton-nucleus collisions. We also propose a next generation of studies of ultra-peripheral heavy-ion collisions, to probe issues in strong-field QED and quantum mechanics, and to make advances in meson spectroscopy.

Utilizing polarized proton collisions up to the highest achievable energy and luminosity, we expect to conduct measurements aimed at untangling the various contributions to the nucleon spin, most prominently the contribution of gluons. One of the proposed upgrades of the STAR detector is driven by the goal of using W-boson production and decay in polarized pp collisions to isolate the flavor-dependence of the sea antiquark contributions to the proton spin, which should help to elucidate the mechanisms by which the sea is produced. Comparison of measured preferences for quark helicity *vs*. transversity will probe effects of relativity and of the coupled evolution of quark and gluon distributions inside a proton.

The measurement programs outlined in this section are organized around basic physics questions and themes, rather than into a natural timeline of experiments. In each section, we indicate what RHIC luminosities and running times, and what STAR detector capabilities, are needed for optimal execution of the program. The anticipated evolution of these capabilities drives the tentative timeline summarized in Table 1 below. Clearly, many of the measurements will begin before the optimum set of detectors is fully deployed. The table also indicates succinctly the physics goals and some important open issues (regarding both technical feasibility and physics interpretation) for each of the proposed measurements, with more in-depth discussions in the following sections. It is the intention of the STAR Collaboration to address the open issues more fully during the coming year. Some of these will require exploratory or complementary measurements.

An important aspect of the STAR scientific program in the years 2004-2007 will be to gain a deeper understanding of the measurements made at full energy by studying the dependence of key observables to beam species and energy ($\sqrt{s_{NN}}$).

Table 1. Prominent aspects of the STAR 10-year physics program, and their needs.

Proposed Measurement	**Physics Goal**	**STAR Upgrades Needed**	**RHIC L Needed**	**Open Issues**	**Proposed Timeline**
Heavy Ion Program					
Elliptic flow for hadrons with no light valence quarks	Evidence of partonic collect-ivity & thermaliz'n	Partial Barrel TOF	4 × present Au+Au	Mean free path of ϕ, J/ψ and Ω in hadronic matter.	2004-7
Upsilon yields and spectra	Temperature and gluon density of partonic matter	EMC completion with preshower	4 × present Au+Au	Is open *b* production needed in addition to interpret Ψ yields?	2004-10
Away-side jet suppression vs. E_T and $\Delta\eta$	Quark vs. gluon energy loss in partonic matter	EMC completion	4 × present Au+Au	Measurement of $\Delta\eta$ in the presence of jet quenching.	2004-10
Coherent J/ψ, open charm photoproduction in UPC	Search for strong gluon shadowing in heavy nuclei	EMC completion, μ-vertex	1—4 × present Au+Au	Hadron absorption in nucleus. Cleanliness of open charm signal.	2004-10
Fluctuation/ correlation studies with PID	Distinguish QCD dynamical effects on temp. and velocity distrib'ns	Complete Barrel TOF	Present Au+Au	Can different non-statistical effects be unraveled?	2007
Away-side jet fragmentation yields, spectra	Search for effects of chiral and $U_A(1)$ symmetry restoration	Barrel TOF, fast DAQ	4 × present Au+Au	Selectivity for "early" hadrons formed in bulk partonic matter.	2007-9
Yields, spectra of high-mass resonances	Duration and properties of the late-stage hadronic medium	Barrel TOF, fast DAQ	4 × present Au+Au		2007-9

Proposed Measurement	**Physics Goal**	**STAR Upgrades Needed**	**RHIC $\mathcal{L}$ Needed**	**Open Issues**	**Proposed Timeline**
Unlike-particle (e.g., π-Ξ) correlations	Spatial and temporal distrib'ns of hadron prod'n	Barrel TOF, μ-vertex, fast DAQ	4 $\times$ present Au+Au		2007-10
Charmed hadron flow and yield ratios	Partonic collect-ivity & charmed quark thermaliz'n	Barrel TOF, μ-vertex, fast DAQ	4 $\times$ present Au+Au	D mean free path. Robustness of subtle thermaliz'n effects.	2007-10
Heavy quark jets; D,B-meson spectra at high p_T	Energy loss of heavy vs. light quarks in partonic matter	Barrel TOF, μ-vertex, fast DAQ	4 $\times$ present Au+Au	Backgrounds for displaced lepton-hadron vertex tag.	2007-10
e^+e^- pair production in UPC	Strong field QED effects	Barrel TOF	4 $\times$ present Au+Au	Is required reduced STAR magnetic field compatible with other parts of program?.	2007-10
$\Lambda, \overline{\Lambda}$ longitudinal pol'n correl'ns	CP violation search	New inner tracker, barrel TOF, fast DAQ	4 $\times$ present Au+Au	Hyperon ID efficiency. Backgrounds and false signals.	2008-10
γ-Tagged jets	Direct measure of parton energy loss	EMC completion; TPC replacement	40 $\times$ present Au+Au	Discrimination against background π^0, fragmentation γ.	2010-13
Direct photon spectrum via $\gamma\gamma$ HBT	Temperature of partonic matter	Replace TPC, pair spectrometer, fast DAQ	4-40 $\times$ present Au+Au	EMC upgrade needed for full 3-D. Un-folding early vs. late collision stage effects.	2012 -
<u>Proton-Nucleus Program</u>					
Direct photon production in p+A	Map gluon densities in heavy nucleus @ x < 0.1	EMC completion	4 $\times$ present d+Au	Background	2006-8
<u>Spin Program</u>					
A_{LL} for photon-jet coincidences	Determine gluon polarization in polarized proton	Full EMC (with preshower @ 500 GeV)	Design $\mathcal{L}$, P=0.7 @ 200 + 500 GeV	Will design beam properties be attained?	2005-9

Proposed Measurement	Physics Goal	STAR Upgrades Needed	RHIC L Needed	Open Issues	Proposed Timeline
Parity-violating asymmetries for $W^{\pm}$ prod'n	Flavor dependence of sea anti-quark pol'ns	Full EMC + pre/postshower; fwd tracker; new TPC FEE (fast DAQ)	Design L, P=0.7 @ 500 GeV	Will design beam properties be attained?	2008-10
Transverse spin + jet fragment'n asymmetries	Quark transversity in polarized proton	Forward hadron calorimeter; barrel TOF	0.3-0.5 × design L, P>0.5 @ 200 GeV	Magnitude of jet fragmentation asymmetries.	2005-9
Transverse spin asymmetries for b-quark and very high p_T jets	Effects of quark mass-dependent terms in QCD; quark transversity	μVertex; forward tracker	2-4 × design L, P=0.7 @ 200 GeV	Is transversity still an issue on relevant time scale?	2010-12
Parity-violating asymmetries for very hard jets	Search for new ultra-short-range interactions	TPC replacement to handle luminosity	10 × design L, P=0.7 @ 650 GeV	Is jet energy reconstructable without hadron calorimeter?	2013 & beyond
Parity-violating asymmetries for W^{+}-n coincidence	Chiral structure of proton: purity of $n\pi^{+}$ configuration	TPC replacement to handle luminosity	10 × design L, P=0.7 @ 650 GeV	Is coincidence with other forward baryons feasible?	2013 & beyond

2.1 Heavy Ion Program

2.1.1 Properties of Partonic Matter

In a broad sense the heavy ion research at RHIC in the coming decade will measure the properties of the matter or system formed in the heavy ion collisions. In the sections below we discuss several of these properties and the measurements STAR can make to address them. Equilibration can be studied by measuring particle yields, however to study equilibration of a fleeting partonic stage, one must use particles produced early and which also decouple sufficiently early that their yields probe the partonic stage. Similarly, to study possible partonic collectivity, one must use particles which decouple early. Since the *b*-quark mass is well above expected temperatures, it is expected to be produced only from the initial collisions and thus can be used as a probe of the early stages of the collision. The early temperature and pressure would be reflected in the direct photon spectrum, but one needs access to direct photons whose energies approach the temperature of the system being studied. The low p_T direct photon spectrum could be accessible for study through the γ–γ correlation signal. This is a very challenging, but important measurement. The nature of the medium produced in RHIC heavy ion collisions can also be studied by observing the affect of the medium on high energy partons produced in hard scattering. A variety of jet studies described below are possible which address this question. Collective motion (flow) and jets are particular correlations which may be used to study the medium formed in the collisions, however in additions one may also study a wide variety of particle correlations and fluctuations among the particles produced in the collisions to further probe the dynamic behavior of the system produced in the collisions. STAR's large acceptance is particularly well suited to such studies.

2.1.1.1 Equilibration and Collectivity

To call the hot dense system formed by the collision of ions at RHIC a Quark Gluon Plasma implies, beyond an explicit role for color degrees of freedom, that this matter has equilibrium thermal properties and that it behaves collectively. In order to gauge whether the system was in thermal equilibrium during the early stage of the collision, one has to either measure the yields and spectra of particles able to escape the system at an early time (i.e., that have small interaction cross sections in partonic or hadronic matter), or study observables sensitive to the integrated time evolution of the system. Examples of particles with small interaction cross sections that may be produced early in the collision are direct photons and di-leptons. These particles can be used as a gauge of the temperature of the early stage, and a long-term measurement program based on them is outlined in subsequent sections of this document. Hadrons containing heavy quarks, which would be created mainly by initial hard parton scattering in the collision, may also probe selectively the properties of the partonic stage. In this section, we outline measurements focusing on heavy hadrons containing strange (exclusively) and/or charmed quarks.

An example of an observable sensitive to the whole evolution of the system is collective flow. The transverse momentum distributions of hadrons, which decouple late from the system, reflect the final temperature at kinetic freeze-out and the acquired collective motion resulting from the integral over the pressure gradient during the lifetime of the system.

The transverse momentum distribution of particles produced in heavy-ion collisions can be characterized by:

$$\frac{\mathrm{d}^3 N}{\mathrm{d}p_t^2 \mathrm{d}\phi\, \mathrm{d}y} = \frac{\mathrm{d}^2 N}{2\pi\, \mathrm{d}p_t^2\, \mathrm{d}y}\left[1+2\sum_n v_n \cos(n\phi)\right],$$

where p_T is the transverse momentum of the particle, ϕ is its azimuthal angle with respect to the reaction plane and y is the rapidity. The second coefficient, v_2, of this Fourier series is called *elliptic flow* and reflects the time integral of the difference between the pressure gradients in and out of the reaction plane.

Figure 14 shows STAR's measured v_2 values for all charged particles as a function of centrality[21]. The boxes show the range of hydrodynamic model predictions. For central to mid-central collisions the observed v_2 values are consistent with expectations from this model. Hadronic cascade models, on the other hand, fail to describe the observed v_2 by more than a factor of three[22]. As shown in Figure 15, the greatest sensitivity of the elliptic flow to the Equation of State (EOS) of the matter treated in the hydrodynamic calculation arises for heavier emitted hadrons, such as protons, with masses far above the freezeout temperature[9,10]. The proton + antiproton $v_2(p_T)$ measured by STAR shown in this figure clearly prefers the EOS that incorporates a phase transition from a QGP to a hadron gas.

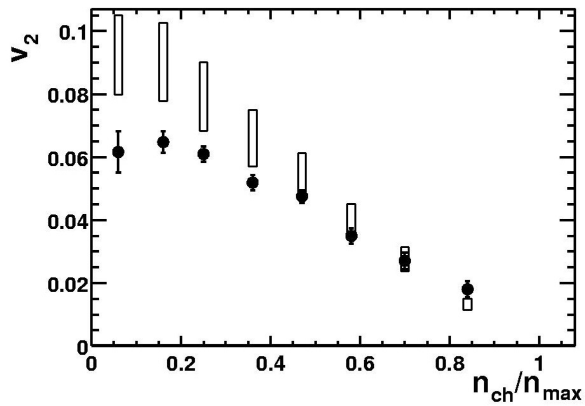

Figure 14. STAR: measured v2 as a function of centrality for Au+Au collisions at = 130 GeV. The boxes show the range of hydrodynamical model predictions.

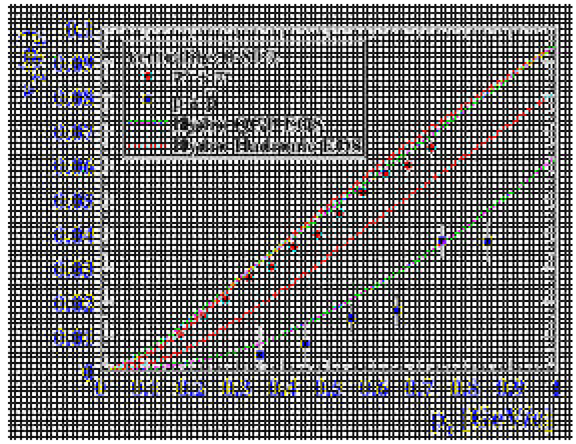

Figure 15. Sensitivity of protons vs. pions to the Equation of State used in the hydrodynamical model calculations.

While the observed proton $v_2(p_T)$ is already suggestive, the measurement of $v_2(p_T)$ of additional heavier particles would further test the viability of a QGP EOS for RHIC collisions. A measurement of the $v_2(p_T)$ for the Ω would tell us whether all the three light quarks are approaching early thermal equilibrium because it has often been argued[23] that the inelastic cross sections of particles like the ϕ-meson, Ω, and J/ψ (containing no *u* or *d* valence quarks or antiquarks) in normal hadronic matter are small (suppressed by the OZI rule). In that case, a sizable $v_2(p_T)$ for these particles could be interpreted as a residue of early partonic collectivity and, depending on the magnitude of $v_2(p_T)$, as evidence for thermalization. Measurements of elliptic flow for particles containing the charm quark are of particular interest because its mass, m_c~1.3 GeV/c^2, is so large that its production is dominated by primordial parton-parton collisions. A finite v_2 value for these particles would indicate interactions with the surrounding quarks and gluons, thus providing a direct probe of the hot and dense matter created in heavy-ion collisions and another strong indicator of early thermalization.

An additional gauge of thermalization is the total charm yield. The expected total charm pair yield due to creation early in the collision via hard parton collisions is shown in Figure 16 for different beam energies from a pQCD calculation. The main uncertainty in this calculation is the charm cross section, which at RHIC needs to be constrained by charm measurements in pp and dA. Figure 16 shows the expected charm yield in the framework of an equilibrium hadron gas (HG) model and an equilibrium quark-gluon plasma (QGP) model. At RHIC energies, the total yield in the HG model is below the initial yield expected from pQCD. An increase of the yield compared to pp, beyond that expected for scaling with the number of binary collisions, would be expected if a QGP is formed.

It has also been suggested that a measure of the charmed quark thermalization may be obtained from the ratios of the yields of the open-charm and charm-strange hadrons [24]. For example the expected ratios of the yields of several charmed particles from p-p and Au-Au with thermalization are shown inTable 2.

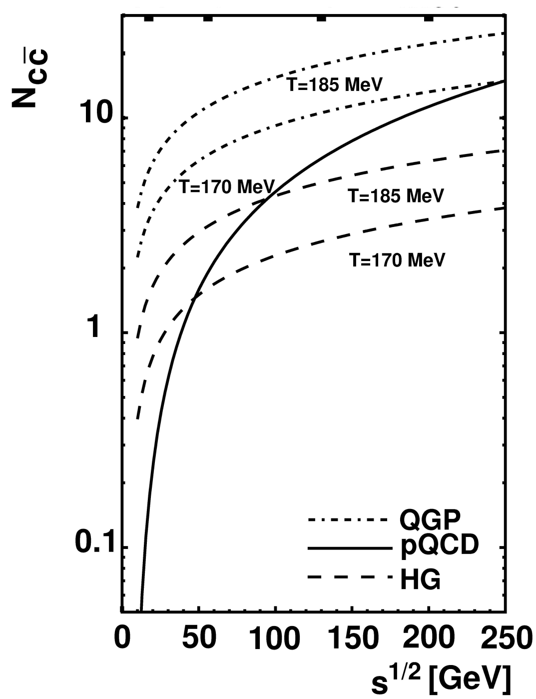

Figure 16. Average yield of charm pairs as a function of beam energy. The calculations are done in the framework of three different models: perturbative QCD (pQCD), equilibrium quark-gluon plasma (QGP), equilibrium hadron gas (HG). The QGP and HG results are shown for two different temperatures.[25]

Ratio	p-p from Pythia	Au-Au thermalized
D^+/D^o	0.33	0.455
D_s^+/Do	0.20	0.393
Λ_c^+/Do	0.14	0.173
J/ψ / D^o	0.0003	0.013

Table 2. Ratio of charmed particle yields at $\sqrt{s_{NN}}$ = 200 GeV for production in p-p collisions (Pythia) and for thermalized production in Au+Au collisions.

Since triggering on open charm is impractical, one needs the highest possible efficiency, low background and large data samples for all the measurements listed above. For open charm measurements, one needs extremely precise vertex resolution. The multi-strange baryon studies also require good efficiency for V^o reconstruction and good particle identification (π/K/p separation) to higher p_T than available just from the dE/dx measurement in the TPC. To acquire the large data sample necessary for these measurements, a faster data acquisition system is required.

To illustrate the detector issues, Table 3 shows the required number of Au-Au central events to observe a 3σ signal (integrated over p_T and y) for the D_s^+ meson with various detector capabilities: 1.) using only the existing TPC and SVT; 2.)adding a high precision micro-vertex detector; and 3.) adding a precison micro-vertex detector plus full barrel time-of-flight. Clearly, even with the full complement of detectors a fast data acquisition system is required to go beyond mere observation of these particles to having measurements over the kinematic variables (y, p_T) and over collision centrality, as well as to making correlation measurements such as flow. Since the requirement for luminosity is modest - the data sample is either minimum bias or central collisions, the 4 times RHIC baseline luminosity upgrade is adequate. Parts of this program have already started, but to complete it will require the detector upgrades indicated. Since even on a technology driven schedule, it is likely that it would take ~5 years to complete the R&D and construction for all the upgrades above, this program will likely extend until the construction of RHIC II.

Detector Complement (Decay Mode)	Au-Au Central Events for 3σ D_s^+signal
TPC+SVT (K_s^o + K^+)	500 x 10^6
TPC+SVT+μVertex	80 x 10^6
TPC+SVT+μVertex+TOF	5 x 10^6

Table 3. Number of Central Au-Au events required for a 3σ signal for the D_s^+.

2.1.1.2 What are the temperature and pressure at early times?

2.1.1.2.1 Upsilon production in Au+Au collisions

In RHIC collisions, heavy quarks (c,b) are produced in the early stages[26] at time scales t $\cong$ 0.2-0.5 fm/c, and they are therefore sensitive to the very high temperature expected in the initial stage of the collision which is estimated to be ~ T $\geq$ 0.3 GeV[27]. At these high temperatures, QCD predicts that gluons, which are massless at zero temperature, acquire an effective mass of the same order of magnitude as the temperature itself, i.e. $m_{gluon} \cong 0.3$ GeV [28]. Thus, the production process gg ® $c\bar{c}$ might be thermally enhanced. However, for gg ® $b\bar{b}$ production, the Boltzman suppression factor is:

$$<b\bar{b}>/<c\bar{c}> = e^{-(2m_b)/(2m_c)} = 0.043$$

so that any thermal $b\bar{b}$ enhancement is unlikely. Thus, generally, b-quark production can be regarded as a pure probe of the early stages of the collision.

In particular, the $b\bar{b}$ bound states ϒ(1S,2S,3S) are the heaviest particles that can be produced at $\sqrt{s}$ =200 GeV, and they are therefore the most sensitive probe of the system when it is close to the initial Hagedorn temperature. Similar to the observed J/ψ suppression phenomenon at SPS, ϒ formation and dissociation rates are sensitive to color screening effects in a dense QCD system. In the upgraded STAR detector, an important physics goal will be to separate the ϒ(1S) and ϒ(2S) states, as their suppression behavior should be different due to different binding radii. The

Υ(2S) with R=0.509 fm is similar to the J/ψ with R=0.453 fm; thus a similar suppression behavior is expected. The Υ(1S) is bound more strongly with R=0.226 fm, and therefore the suppression in this case should be weaker. In fact, the expected break-up temperature of the Υ(1S) is T=391 MeV[29] (T=260 MeV for the 2S state). Thus possible observed suppression behavior would give an indication whether the system reaches a high Hagedorn temperature or not.

In addition to the initial temperature, Upsilon formation is also sensitive to the initial gluon density. At 200 GeV, ~90% of all Upsilon mesons are formed by gg, and ~ 10% by $q\bar{q}$. Four different mechanisms contribute. Three processes have only one gluon in the final state ($gg\rightarrow\Upsilon g$), namely color singlet $b\bar{b}$ fusion (strength ~(α^3/p_T^8), color octet gluon fragmentation (~(α^5/p_T^4) and color octet gluon exchange (~(α^3/p_T^6). The fourth process, namely color singlet gluon fragmentation (~(α^3/p_T^4) produces three gluons in the final state ($gg\rightarrow\Upsilon ggg$) and may well be suppressed in a very dense, possibly even saturated gluonic system such as the primordial phase of a Au+Au collision.

For STAR, compared to the measurement of the J/ψ, the Upsilon measurement is very advantageous for three reasons: *a.)* The large rapidity coverage of the detector gives STAR a unqiue capability for this measurement at RHIC; *b.)* The STAR EMC resolution (ΔE~17%/$\sqrt{E}$) is about a factor 2 better for leptons from Upsilon decay than for leptons from J/ψ decays; *c.)* The trigger requirement of selecting two high p_T (> 3 GeV/c) leptons rejects background such as correlated semileptonic D meson decays by several orders of magnitude, which is not possible for the J/ψ.

The total numbers of observed Upsilons seen by STAR by the year 2010 is estimated as follows. We assume an integrated luminosity of ~3.1 nb^{-1}. This includes a RHIC up time of 40%, STAR up time of 70%. Furthermore, an acceptance of 34% is assumed, which corresponds to a full barrel EMC, but does not take the endcap EMC into account. If we make a conservative estimate that he nuclear absorption factor is α=0.9, then we estimate a total number of Upsilons will be N $\cong$ 3500 by the year 2010. The relative yields of the Υ(1S), Υ(2S) and Υ(3S) are in the ratio of 100:39:10. This assumes operation of an EMC high tower trigger at Level-0 with a threshold of 3.5 GeV, which was studied in simulations and found to be > 90% efficient. The DAQ and trigger live time have been assumed to be 50%. If the nuclear absorption factor is increased to 0.95 or 1.00, the estimated sample is increased by factors of 1.6 or 2.8, respectively. This estimate also assumes a β*=1 m, i.e. all events occur within z = 30 cm of z = 0, and are useful for analysis.

Recording minbias events without a trigger, the number of detected Upsilons would be reduced by a factor of ~ 63 using STAR DAQ100, and by a factor of ~318 using an unchanged STAR DAQ system. Thus the Upsilon measurement in this case would not be feasible. Figure 17 shows the expected Upsilon yield by the year 2010. The Upsilon signal was simulated using the full STAR reconstruction chain with the full STAR detector geometry in GEANT 3.14. The background corresponds to real Au+Au events at 200 GeV recorded in 2001 (2.4×10^6 10% central and 2.3×10^6 minimum bias events). The analysis details are described in reference 30. The error bars contain statistical and systematic errors (also described in reference 27). For the hadronic part of the background ($\pi^+\pi^-$ unlike-sign pairs), an EMC hadron suppression factor of 1/200 was assumed[31] for E > 3.5 GeV at 90% electron efficiency (left), and 1/2000 at 50%

electron efficiency (right). The signal/background ratio is 1:1 and 6:1, respectively. In addition to lepton identification using the STAR EMC, a TPC dE/dx cut (ref. 30) was applied, using the TPC slow simulator for dE/dx simulation. Candidate tracks were preselected using a p > 3 GeV/c cut to suppress background electron pairs from correlated semileptonic decays of D mesons. Both statistical and systematic errors are shown. The systematic errors contain the measured p_T resolution (B=0.5 T), hadron/lepton mis-identification for TPC dE/dx and a 10% error for the applied cuts.

The expected mass resolution with TPC alone is Δm = 0.340 GeV for the Υ(1S) alone, and Δm = 0.610 GeV for the combined Υ(1S,2S,3S) family of states. The masses are m = 9.460 GeV, 10.023 GeV and 10.355 GeV for the 1S, 2S and 3S state, respectively. Thus, for a possible 3σ separation of the 1S and 2S states, the STAR mass resolution would have to be improved by a factor of ~2, which should be feasible using an upgraded microvertex detector.

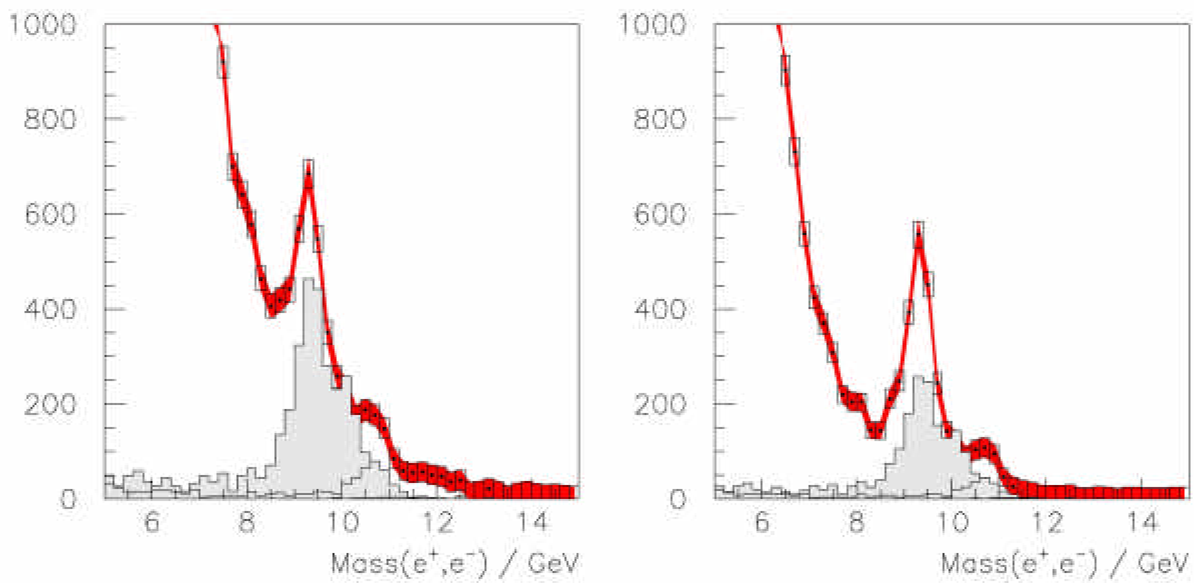

Figure 17. Simulated invariant mass spectrum for e^+e^- pairs detected in STAR for 200 GeV Au+Au collisions in an assumed integrated luminosity of 3.1 nb^{-1} for two different hadron suppression factors as described in the text.

2.1.1.2.2 Two-photon HBT

It has long been recognized that measurements of the yields and spectra of penetrating particles, such as leptons or photons, can provide a more quantitative probe of the early stages of the collision than those of hadrons and without the ambiguities regarding hadron interaction probabilities during the later stages. For the existing RHIC experiments direct photons with transverse momentum of 1.5 GeV/c or greater should be accessible by the usual method of measuring all photons, then subtracting all known sources of non-direct photon background. However, the interesting range of softer photons, necessary for the study of properties of the early partonic phase is vastly populated by background photons from π^o decay. In this region, an unambiguous means of observing direct photons is by measuring the HBT peak in the $q_{invariant}$

distribution of photon pairs. The key point in this approach is that only direct photons, emitted from the interaction system, will give rise to an HBT peak consistent with a size of several Fermi. Thus direct photons can be identified at all photon energies and transverse momenta, especially those where the π^0 decay photons are too numerous for a direct subtraction to determine the direct photon yield.

It seems quite feasible in an upgraded version of STAR to observe the HBT peak in the $q_{invariant}$ distribution for photon pairs. This allows the measurement of the flux of direct photons and their distribution in rapidity and transverse momentum. Since photons are emitted without subsequent interaction from all phases of the interaction, including the partonic phase, the experiment will measure properties of the early time partonic phase as well as the later hadronic phase. The direct photon spectra are sensitive to the properties of the early stage (QGP) as well as to the hadron gas produced in the later period of the collision.[32] While the analysis is complex, it appears likely that the two stages can be separately identified from the direct photon spectra. In any case, new and quite different information on the dynamics of the collision will be obtained. If three-dimensional HBT analysis can be done, unique properties of the QGP phase can be studied, such as its spatial and temporal dimensions. Many theoretical studies have focused on the physics of the direct photons, which unfortunately have so far been experimentally inaccessible.

The new compact TPC for high luminosity operation in STAR would provide central tracking in the required setup. Outside this TPC we would place three or four annular layers of TPCs. Each would cover the full STAR ϕ and rapidity range at successively larger radii. They would be separated by radiators of approximately 0.6 radiation lengths. These TPCs would function as "pair" spectrometers for the photons converting in the radiators. At the outside of these TPCs we would have the STAR time of flight detector and finally the EMC. The large (0.6 radiation length) radiator thickness required degrades the energy measurement, but by measuring all of the visible energy emerging from the conversion, useful photon identification is possible. Simulation studies show that $q_{invariant}$ can be measured adequately to observe the HBT effect and extract the direct γ spectrum. The advantage of the large converter thickness is improvement in event rate. This arrangement would permit the measurement of many of the usual STAR physics variables, which could then be correlated with direct photon studies.

For the calorimeter to be useful for HBT studies, the current EMC would have to be augmented with additional equipment aimed at good resolution for the .5 to 1.5 GeV energy range for photons. "Inexpensive" ways of accomplishing this are under study. If the calorimeter can be so augmented, it may be feasible to carry out 3D HBT and determine the size and time duration of the early stage of the collision. The TPC pair spectrometer by itself seems to be adequate for only a $q_{invariant}$ study.

Finally we note that an experiment with this photon (and charged particle) detection capability would open up the study of particle decays and resonance physics involving photons in the final state.

The extraction of the HBT correlation signal requires about 10^9 Au-Au events. Although acquiring this many events does not require the full RHIC II luminosity, the upgrade plan for STAR couples that luminosity to the TPC replacement, which *is* required to provide the space for the photon spectrometer. That makes this study a RHIC II activity. To record the required number of events in a single run also requires an upgraded data acquisition system.

2.1.1.3 The QCD medium, velocity fields and dissipation

Beyond measuring the bulk equilibrium properties of matter produced in the early stages of RHIC collisions, it is important to probe the influence of QCD dynamical processes that may be manifested in fluctuations and correlations among the emitted particles. The concepts in this section are discussed more fully in the STAR time of flight proposal[33], section 3.3.

To unfold correlations and extract the information they carry, it is necessary to separate the effects of various underlying dynamical/dissipative processes which may result in large scale collective motion (global structure in the overall velocity field of all the produced particles) or more localized effects such as local temperature (thermal) fluctuations which may affect the motion of smaller groups of particles. Examples of large-scale velocity fields include radial flow, elliptic flow, and Bjorken expansion. These are specific examples of a more general concept. The structure of the velocity field observed in the final state (the "velocity structure") is expected in general to be complex, since it contains contributions from the entire history of the collision.

Thermal and velocity correlation structures show up in heavy ion collisions as non-statistical fluctuations in event-wise averaged global quantities (*e.g.*, event-wise mean p_T) and in two-particle momentum-space correlations[34]. Little is known at present about the detailed velocity structure of RHIC events. Distinguishing velocity structure and thermal fluctuations from equilibrated thermal energy in the hadron system requires particle identification (mass measurement) of pions, kaons, and protons for transverse momentum substantially beyond ~1 GeV/c.

Separate determination of velocity and thermal structures in RHIC events is essential because the velocity structure represents an otherwise unknown, fundamental degree of freedom of the collision system and because velocity and temperature fluctuations are affected differently by QCD dynamics. For example, localized energy perturbations (*e.g.* QGP droplets) could produce "hot spots" which would be manifest in the data as local temperature fluctuations with respect to a characteristic scale in pseudorapidity and azimuth. Dynamics which produce structured pressure gradients in the early collision should produce event-wise (large scale) fluctuations in the velocity field. Minijets are expected to produce both local temperature and velocity fluctuations. Whether QCD dynamical processes result in thermal or velocity structure, both lead to momentum-space fluctuations and correlations in the unidentified hadron momentum distribution. Unambiguous interpretation of the resulting fluctuation and correlation structure with *unidentified* particles simply is not possible.

Analysis of first RHIC data by STAR has already revealed that Au+Au collisions have a complex correlation structure, including large-scale two-particle correlations in p_T, η, and ϕ, which provide direct access to a range of QCD phenomena available from no other experimental source. Charge-independent (isoscalar) and charge-dependent (isovector) correlation structures already being observed[35] in distributions of relative two-particle transverse momentum (up to ~2 GeV/c), pseudo-rapidity ($\eta_1 \times \eta_2$ up to 2 units), and azimuthal angle ($\phi_1 \times \phi_2$ up to π radians) are comparable in size to the STAR TPC acceptance. To fully extract the information these correlations carry and use it to understand the role of nonperturbative QCD in Au+Au collisions at RHIC requires particle identification (π, K, p) over the full STAR TPC acceptance, over a momentum range substantially exceeding that for dE/dx PID in the TPC+SVT. This can only be accomplished in a cost effective way with the addition of the proposed STAR barrel TOF detector based on multi-gap resistive plate chamber technology.

The data sample required for these analyses is modest – a few million events – so that the existing luminosity and DAQ are adequate. The particle identification provided by the full barrel time-of-flight system is essential. This sets the time scale for these measurements at 2006 and beyond.

2.1.1.4 What is the gluon density of the partonic matter formed in RHIC collisions?

Twenty years ago Bjorken[36] proposed that the energy loss of fast partons in matter is related to the temperature and density of the medium. This led to the proposal of studying jet production in high energy hadronic collisions as a means of probing the state of the matter generated in by the collisions – the events are self-analyzing. At high $\sqrt{s}$, high Q^2 scattering is frequent, resulting in statistically robust jet-related observables. High Q^2 processes occur early in the collision, thus the jets probe the system at its earliest, hot and dense phase. While Bjorken's initial consideration of elastic scattering of partons generated effects too small to be observed, further theoretical study[37] revealed that induced gluon radiation (bremsstrahlung) could result in significant energy loss ("jet quenching") making observation and measurement of it an experimental possibility and providing access to the color charge density of the medium at early times.

The RHIC experiments have recently made significant progress towards this goal. Studies of the inclusive distributions and correlations of high p_T hadrons in nuclear collisions reveal that:

1. Inclusive yields are strongly suppressed in central collisions[2,5]
2. Elliptic flow is large[4]
3. Fragmentation of observed jets for all centralities is similar to that for p+p collisions[3,4]
4. Back-to-back jets are strongly suppressed in central collisions[3]

These phenomena are consistent with a picture in which the core of the collision zone is very dense and opaque to jets due to partonic energy loss effects. In this picture the jets that are observed by the detector are strongly biased towards those generated on the surface of the reaction zone and heading outwards, fragmenting in vacuum, while jets heading inwards are strongly suppressed and less likely to be observed. However, these phenomena may also be consistent with strong modification of the wave function of heavy nuclei relative to that of the proton, due for instance to gluon saturation effects[38]. Discrimination between initial and final effects as the origin of the suppression phenomena was made by the recently completed d+Au control experiment at RHIC, which decided in favor of final state interactions of jets or their fragments in the dense medium generated in heavy ion collisions[1].

While it is now well established that the high p_T suppression and flow phenomena are final-state effects, there are still important questions that must be addressed in order to establish specifically partonic energy loss as a precision, textbook tool to probe the medium:

1. What are the relative contributions of partonic energy loss and absorption of hadronic fragments of the jet?
2. Can the energy loss of jets be directly observed rather than inferred from suppressed cross sections?
3. Can the partonic energy loss be varied in a controlled way through variation of the color charge coupling to the medium (light quarks, heavy quarks, gluons)?
4. Can the effects be turned off in a controlled way?

While the data necessary to address the first question may already be in hand (awaiting more advanced theoretical calculations), addressing the remainder will require extensive measurements at high integrated luminosity, together with detector upgrades. In the following we describe three key experiments in this direction. As these measurements confirm basic predictions associated with a QGP phase, they will also permit a more quantitative determination of the gluon density in this unique matter.

2.1.1.4.1 g+jet

The Compton process q+g $\rightarrow$ γ+jet was proposed by Wang and Huang[39] as a means of constraining the scattering kinematics of jet production in nuclear collisions, since the photon does not interact with the medium. The energy loss can be observed directly, through comparative measurements of hadron distributions from the recoil jet in p+p, p+A and A+A collisions. We expect this to be the definitive measurement of jet quenching, making it a high precision tool for studying the medium.

Direct photon measurements are challenging, especially in the environment of heavy ion collisions. Backgrounds from other photonic sources are large (especially π^0 and η decays), though the strong hadron suppression observed in nuclear collisions will be of assistance in this respect. QCD backgrounds (fragmentation photons) are also a significant background at RHIC for $p_T^{\gamma} < 10$ GeV/c [40]. Standard direct photon measurement techniques, in particular isolation cuts, may be difficult to apply in heavy ion collisions. STAR is aware of the technical obstacles to this measurement. With the commissioning of the Electromagnetic Calorimeters and first analysis of data from them we are beginning to address these issues. With the aid of data and simulations, we will explore, for example, the background suppression effectiveness of selecting events with an EMC transverse shower profile (measured in the shower-maximum detector) characteristic of a single photon, and with a cut on the maximum number of associated particles above a p_T threshold in the immediate angular vicinity. While awaiting the outcome of such studies, we restrict our considerations here to signal rates and the integrated luminosities required for statistically robust measurements.

The basic cross sections can be extracted from Wang and Huang[39]. Inclusive photon differential cross sections for central Au+Au collisions at $\sqrt{s}$ =200 GeV are about 6 μb/GeV at p_T =10 GeV/c and 0.6 μb/GeV at p_T =15 GeV/c. Under the assumption that the integrated luminosity for 200 GeV Au+Au collisions through 2009 is 10 nb^{-1}, measurement of a high quality direct photon inclusive p_T spectrum out to 15 GeV/c and beyond will be possible. The energy loss measurement, however, requires the coincidence between the photon and hadrons from the recoiling jet. The simplest measurement is the coincidence with a single leading hadron from the jet, which however must have sufficient p_T to dominate the incoherent background. Estimates from Wang and Huang are that only about 0.1% of the recoiling jets fragment into a hard leading hadron above background. Other jet observables, in particular multiparticle correlations of high p_T hadrons, are currently under active development. Roughly speaking we can expect that the measurable coincidence cross sections will be lower than the inclusive photon cross sections mentioned above by a factor 100 or more, so that this measurement will require the high integrated luminosities accessible only during the RHIC II era. By 2013, we can anticipate getting a useful start on the coincidence measurements for photon p_T up to about 10 GeV/c for Au+Au. The baseline measurements in p+p and p+Au will be made naturally in association with other high priority physics goals (gluon polarization in the polarized proton, and determination of gluon densities in cold heavy nuclei) outlined for these systems elsewhere in this report

2.1.1.4.2 Heavy quark jets

Dokshitzer and Kharzeev[41] have proposed that the energy loss of heavy quarks in a dense medium is less than that of light quarks due to the dead cone effect: collinear radiation is suppressed by kinematic effects. For p_T ~10 GeV/c and above this effect is calculable in pQCD, thus the measurement of heavy quark-tagged jets and the relative yields of D and B-mesons at high p_T offer additional tests of the partonic energy loss picture.

Cross sections for heavy quark production at RHIC energies have been calculated by Ramona Vogt of the Hard Probes Collaboration[42].The cross section for $b\bar{b}$ production within the STAR acceptance is ~20 μb/GeV for central Au+Au collisions at $\sqrt{s}$=200 GeV, so that 10 nb^{-1} generates about 200K $b\bar{b}$ pairs.

One possibility for a rate measurement utilizes the CDF technique[43] for semi-leptonic decays (branching fraction ~10%), in which the hard lepton (in STAR's case an electron) generates a trigger in the EMC and the heavy quark is tagged by a displaced vertex of an intermediate p_T hadron with the lepton track. Combinatorial backgrounds are assessed by measuring the rate of displaced vertices in the unphysical region behind the primary vertex (i.e. against the direction of flight). Backgrounds for $\bar{p}+p$ events at the Tevatron are modest. Rough calculations of background rates for heavy ion collisions at RHIC, utilizing the resolution of the proposed STAR microvertex upgrade and CDF cuts, give about 3 background vertices per lepton-triggered event. More detailed simulations and optimization of the cut space need to be investigated (increasing the p_T of the hadron candidates, increasing the decay distance cut, etc.). It may be possible to reduce the background rate considerably relative to this naïve estimate. If a low background rate can be achieved, then the jet recoiling away from this tag can also be studied as an unbiased sample of heavy quark jets, opening up a large new area of study.

2.1.1.4.3 Energy loss of quark vs. gluon jets

Yet another measurement of partonic energy loss may be achievable by exploiting the difference in coupling to the medium of quarks and gluons, with gluons coupling more strongly by 9/4, the ratio of the Casimir factors. It is well established that triggering on leading hadrons is biased toward quark jets, which are known to fragment harder. A program to assess this bias quantitatively is underway, and less biased triggers are being investigated. Bias towards gluon jets may be achievable by exploiting the x-dependence of the parton distribution functions and the broad coverage in pseudorapidity η of the STAR detector. The relative fraction of q-g vs g-g scattering producing dijets may be tunable by exploiting both the E_T scale of the jets and the pseudorapidity difference $\Delta\eta$ between them. (However, jet quenching of the away-side jet in the hot dense matter produced may seriously complicate any such selection.) Because this is a highly differential measurement, it will require high integrated luminosity, though quantitative estimates are not available at present.

2.1.2 Are Fundamental symmetries restored/broken in the partonic matter?

One of the most important goals of RHIC during the coming decade will be to probe the effect of the new matter produced in heavy-ion collisions on basic symmetries of the strong interaction. It is a very significant experimental challenge to devise suitable handles on symmetries in matter produced so fleetingly, and the possible avenues described in this section are thus necessarily more speculative than those in other sections. But a convincing demonstration of CP violation, or of chiral and $U_A(1)$ symmetry restoration, would provide a second RHIC discovery of comparable impact to the establishment of the QGP itself.

2.1.2.1 Search for CP violation

It has been proposed that violation of CP symmetry by the strong interaction may occur in metastable regions produced in heavy ion collisions. This idea has been related in a paper by Kharzeev et. al[44] to the restoration of $U_A(1)$ symmetry as a second order phase transition. The observation of such an effect would have widespread implications. It would of course be the first Parity and CP violation observed in the strong interaction and would likely lead to a better understanding of why CP violation does not normally occur in strong interactions even though seemingly allowed (the "Strong CP" problem). It would also provide important insight into the nature of the phenomenon of spontaneous symmetry breaking in general. Finally, it would also be a strong indication of a chiral symmetry restoration in heavy ion collisions.

One proposed method through which this may be observed is by looking for CP violating asymmetries in produced particles' momentum space distributions[45]. A second possible method is to look for correlations in the longitudinal polarization of hyperons. The former method is tied to certain configurations of the CP violating regions and is therefore more limited in its ability to discern a CP violation, but it has the advantage that the current STAR setup is adequate (the number of central Au+Au events needed for a meaningful study is at least several $x\ 10^7$). The latter method is more robustly tied to the theory, but it is more difficult experimentally. With current (very rough) theoretical guidance on signal strength, we estimate that if the efficiency for identifying hyperons can be made as high as 30%, a meaningful study will require ~2 $x\ 10^8$ central Au-Au events. Clearly, good secondary vertex detection for hyperon-like lifetimes and an upgraded data acquisition are critical. Also for this latter method, more detailed studies of possible backgrounds which may imitate a CP violation are needed and should be performed in the coming year.

To record the required event sample for this study, an improved data acquisition system is required. Also, any improvement in proton identification, such as that which would be provided by full coverage time-of-flight will help increase the Λ^{o} reconstruction efficiency and reduce the background. Since the data sample is simply minimum bias Au-Au events, no upgrade in luminosity is required. The needed STAR upgrades would be available in ~5 years on a technology driven schedule.

2.1.2.2 Chiral symmetry and $U_A(1)$ restoration: away-side jet fragmentation.

As evidence for the formation of deconfined partonic matter in RHIC heavy-ion collisions accumulates, one of the most important issues to address more sharply in experiments is the status of chiral symmetry breaking in this partonic matter. Most discussion of direct evidence for chiral symmetry restoration has focused on the search for mass shifts in hadrons containing *u*, *d* or *s* valence quarks that emerge from these collisions. A search ia complicated by the following suspicion: if a QGP is fleetingly formed in the collision, then the bulk of hadrons observed will be produced during its waning moments, and their production spectra and properties will be further modified in subsequent stages leading to chemical freezeout. There is hope in studying dilepton invariant mass spectra that we can see effects arising from the early (pre-freezeout) decay of ρ-mesons or other hadrons into non-strongly-interacting daughters, but the experiment may still be sensitive primarily to the early decay of late hadrons. It is therefore important to complement global searches for hadron mass shifts in the debris of RHIC collisions with attempts to enhance more selectively the role of hadrons formed early in the collision, and in the midst of bulk partonic matter.

Recent STAR results provide a basis for a speculative approach to achieving such an enhancement. The strong suppression of away-side, but not near-side, jets in central Au+Au collisions, observed via the azimuthal opening angle distribution for high-p_T hadron pairs[3], suggests two important features of the collisions: (1) observed high-p_T hadrons most likely signal a hard parton scattering event occurring near the surface region of the collision zone which can serve as an effective tag of away-side partons that are forced to traverse substantial amounts of the matter produced in the collision; (2) the tagged away-side partons do not fragment as they would in a vacuum, and in particular, they do not yield the expected frequency of high-momentum hadronic fragments. The pQCD interpretation of these observations is that the away-side parton loses substantial energy to gluon radiation in traversing the dense gluon-rich matter in the collision zone. If these radiated gluons form a number of relatively soft mini-jets in the azimuthal region opposite the tagging high-p_T hadron, their fragmentation may well provide a source of early hadrons formed within the QGP. The large acceptance of STAR is very well suited to mapping out the in-medium fragmentation functions of these tagged away-side partons, and to searching for possible effects of chiral symmetry restoration on the mass spectra and particle production ratios among the hadron fragments. It is clearly not possible to cleanly associate individual hadrons on the away side with the scattered parton or with the collision background, but one can look for statistically meaningful differences in hadron spectra opposite the tagging hadron from those observed in the same event transverse to the tagging hadron direction. The same sort of comparison can then be made in d+Au or p+Au collisions, to provide a baseline measurement in the absence of a partonic medium. It is a major goal of STAR for the coming years to map out these away-side fragmentation functions, with particle identification, as a function of the pseudorapidity difference between the tagging and away-side directions (as this will influence the balance between quark and gluon away-side partons).

Since even modified hadrons formed within chirally restored matter will evolve back toward canonical masses and decay properties as they exit this matter, it is still important to emphasize either early non-hadronic decays of the hadrons or hadron production ratios in searching for symmetry restoration effects. For example, it would be useful to compare $e^+ e^-$ invariant mass spectra opposite *vs.* transverse to the tagging high- p_T hadron. The potentially mass-shifted ρ-mesons one might sample this way have moderate $p_T \sim 1$ GeV/c, still small enough that the time-dilated decay length permits significant decay probability before the meson has exited the collision zone, but large enough that STAR's electromagnetic calorimeters can aid in electron identification. A chiral symmetry restoration mass shift of the φ-meson might show up most clearly via anomalous φ/K production ratios opposite a leading-hadron φ tag (to emphasize $s\bar{s}$ partonic final states, for which a kaon tag is considerably less selective). Kaon identification at interesting momenta for this study would be provided by the proposed STAR TOF upgrade. The theoretically suggested restoration of $U_A(1)$ symmetry in the QGP would affect the η and η′ masses[46], and might be manifested by anomalous yield ratios of these particles in comparison to π^0 opposite a high- p_T hadron. Clearly, for such studies completion of the barrel and endcap EMC's is crucial.

This program of measurements requires very large data samples to enable the subtraction of yields transverse to the tagging particle from those (only slightly larger yields) opposite in azimuth, and to permit study of individual hadron types and low-branching-ratio decay modes. Some of the data can be collected with an EMC-based high-tower trigger, but this will be of limited help for example in emphasizing strange-quark jets. Thus, a large sample of minimum bias and central Au+Au events will also be needed, after completion of the proposed TOF barrel and DAQ upgrades. Central collision samples of several hundred million events would be needed for meaningful analyses of the sort of selective hadron channels discussed above.

2.1.3 What are the properties of the hadronic medium after hadronization?

To interpret the measurements at RHIC will require an understanding of the nature of the late stage of the collision and its effect on measured quantities. Both identical and non-identical two particle correlations provide a means to probe the late stage evolution. Additionally, studying the yields and spectra of resonances with a variety of lifetimes in the range of the collision lifetime, a variety of masses, widths and decay modes provides a powerful set of tools for understanding the late stage environment[47].

2.1.3.1 Two-Particle correlations

While the exciting high- p_T observations at RHIC show clear deviations from similar measurements at lower energy, and conform qualitatively to QGP-based expectations, the picture extracted from the bulk of the particles (mostly at $p_T < 2$ GeV/c) is significantly less clear. This is important, as the QGP, by definition, is a bulk-large-scale, low-Q—collective-system state, which might naturally be expected to manifest itself in collective, low- p_T observables.

High-p_T fragments/partons probe the collective system (QGP?), but bulk/low-p_T observables are the remnants/manifestations of the system itself. The difference is that the latter reflect the evolution of the system. Even if convinced of the generation of a QGP, we must not be satisfied until we understand its properties and evolution.

Multiple bulk/global observations (spectra, elliptic flow, meson HBT, non-identical particle correlations, short-lived resonance yields) point to a consistent picture of an explosive system, dominated by collective flow fields superimposed on thermal motion. (The question of true thermalization is addressed elsewhere.) In particular, the correlation analyses indicate that the system evolves quite quickly from participant overlap to kinetic freeze-out (~ 9 fm/c), and that the freeze-out process is also rather fast (~2 fm/c). These observations disagree with the expected increase in system timescales associated with a simple QGP formation hypothesis. Indeed, a hadronic phase—even one which follows or replaces a partonic one—would naively appear to be ruled out, as the expected timescales associated with the evolution of such a phase are too long.

Soft particles are the remnants of the bulk system created in heavy ion collisions. Until low-p_T observables display strong energy dependence at some threshold energy, or until the consistent picture they suggest is theoretically understood, it is difficult to make strong statements about discoveries, based upon them.

Future progress in this area is likely to be theory-driven. However, measurements which would help clarify the picture include: high-statistics, minimum-bias study of the Omega (multi-strange flow) and charmed particles as indicated in a previous section. Unlike-particle correlations give information on the relative space (time) when the particles are emitted. Although progress has been made in this study, the necessity of correlating particles of different mass at the same velocity requires particle identification over a wide momentum range. To broaden this study particle identification at higher p_T is required. To access information on the multi-strange baryons, (π-Ξ correlations for example) large enough data samples are required. The full barrel time-of-flight, faster data acquisition system, and micro-vertexing capable of detecting charm decays would allow these studies to be performed. This means the time scale for the full program will likely extend to the RHIC II construction era.

2.1.3.2 Resonances

Resonances have a range of lifetimes on the order of the collision fireball lifetime, therefore measuring their yields and spectra can provide information about the conditions of the hot and dense hadronic medium. Further, the large number of resonances with a range of quantum numbers, masses, quark content, and decay products provides a unique tool for probing the hadronic medium formed in the late stages of the collisions of heavy ions. In order to interpret measurements of the properties of the partonic stage, it is vital that we understand the nature of the final hadronic stage of the collision and its possible effects on our measurements. Mass shifts and width broadening are also predicted medium effects on resonances. Observations of the e^+e^- decay channel should be more sensitive to these because of the smaller interactions of the decay leptons with the medium.

Calculations for the time span between chemical and kinetic freeze-out can be done by the observation of a signal loss in the hadronic decay channel by rescattering of the decay products. Direct comparison of resonance production between elementary p+p, p+A collisions and A+A interactions may show the influence of an extended reaction volume around the resonances. The question of whether A+A collisions are a superposition of elementary collisions can be studied.

STAR has already measured several resonances (ρ, Δ, K*(892), Σ(1385), Λ(1520), ϕ) in the hadronic decay channels in p+p and heavy ion collisions. To complete this new program, it is necessary to measure higher mass resonances with enough statistics to plot transverse momentum spectra. Improved particle identification from the proposed MRPC barrel TOF system will greatly increase the sensitivity of data collected for many resonances. Further, the electron tag provided by combining the TOF measurement and the TPC dE/dx information should allow access to e^+e^- decay channels. Increased data acquisition speed will allow accumulation of the required large data samples for a full program of detailed measurements. Since most resonances of interest are produced copiously in Au-Au collisions, this program is dependent more on the detector upgrades than on RHIC luminosity improvements.

The time scale for the required STAR improvements means that this program will likely extend until the RHIC II construction era.

2.1.4 What are gluon densities in normal nuclear matter?

Among RHIC's unique properties is its ability to measure gluon shadowing at low Bjorken x in heavy nuclei directly, using a hadronic probe. Theoretical expectations for gluon shadowing vary widely ***(refs)***, but measurements must be sensitive to 10-20% effects in Au at x~0.1. While this measurement will be carried out using a variety of probes (inclusive hadrons, dihadrons, dijets, etc.) STAR's golden channel for this measurement is the Compton channel $q+g\rightarrow\gamma$+jet. Consideration of direct photon backgrounds and cross sections in the STAR acceptance leads to the conclusion that this is a multi-year program requiring high luminosity. The kinematic reach at RHIC is approximately $x > 0.02$ (for the same reasons as for the measurement of ΔG). A statistical precision of 5% at $x = 0.02$ will be achieved for a single heavy nucleus in 10-20 weeks of RHIC running.

Forward going jets detected in forward hadron calorimeters now under study could also be used to probe the gluon density in a heavy nucleus. Since the Color Glass Condensate (CGC) cannot explain the suppression of high- p_T particle production at mid-rapidity in Au+Au collisions, a detailed understanding of possible modification of the gluon structure functions for nucleons bound in heavy nuclei remains an important issue. A quantitative understanding of the gluon density in a heavy nucleus is essential to a detailed calculation of the dynamics of ultra-relativistic heavy-ion collisions. The first measurements providing sensitivity to possible gluon saturation phenomena were made at STAR at the end of d+Au collisions in RHIC Run III. The centrality dependence of the yield of forward ($|\eta|$ ~ 4) π^0 mesons was measured in both the deuteron and Au beam directions. Analysis of that data is underway. Full reconstruction of the forward jet allows improved reconstruction of the initial-state parton kinematics, thereby enabling the determination of possible modification of the gluon field as a function of Bjorken x.

2.1.5 Ultra-Peripheral Collisions

Ultra-peripheral collisions (UPCs) are electromagnetic interactions that occur at impact parameters larger than twice the nuclear radius, where no hadronic interactions are possible.

Both two-photon and photonuclear interactions are of interest. Because of their large charge, heavy ions are intense sources of photons; with the Lorentz boosts, two-photon energies up to 6 GeV are achievable, and photonuclear interactions can be studied with fixed target equivalent photon energies up to ~ 1 TeV. The unique geometry and nuclear environment allow for many unique studies. We list here 4 topics where we expect to make significant contributions where we expect to make significant contributions in the next decade of research at RHIC.

2.1.5.1 The gluon distribution in heavy nuclei.

The gluon distribution of heavy nuclei is not well understood. Using deep inelastic scattering (DIS), significant shadowing has been observed for *quark* distributions. However, the *gluon* distributions are not measurable with DIS. Studies using hadronic interactions are subject to uncertainties due to higher order corrections and the Cronin effect. Photoproduction studies avoid these problems. STAR will study the gluon distribution of heavy nuclei using two photoproduction channels: coherent J/ψ production, and open charm. Without shadowing, the J/Ψ cross section is about 0.3 mb, resulting in a projected sample of 66,000 J/Ψ produced during the 2004 run (for 219 μb^{-1} total luminosity). The useful branching ratio (to e^+e- and $\mu^+\mu^-$) is 6% so after acceptance about 1200 J/Ψ will be detected in STAR. The total cross section isn't very sensitive to shadowing but the rapidity distribution is so if gluon shadowing is large, as predicted in HIJING and the diffractive model of Frankfurt and Strikman[48] then shadowing may reduce mid-rapidity J/Ψ production by as much as 40%. If shadowing is this large, it should be observed quickly (in the period 2004 - 2005). A detailed study of J/Ψ production with and without nuclear breakup, to measure gluon shadowing as a function of *x* will require considerably more time and data. These studies require an efficient and selective J/Ψ trigger, which can be a combination/evolution of the existing UPC topology and J/Ψ triggers. The calorimeters will be essential for help in selecting electron pairs.

To lowest order, photoproduction of open charm occurs through photon-single gluon fusion. This is relatively clean theoretically and has high rates. The disadvantage (compared to the J/Ψ) is that the analysis is more complex. Open charm can be studied via its semi-leptonic decays and separated vertices. This requires the silicon microvertex detector for vertexing, and the full electromagnetic calorimeter for the electron identification. The major background is due to charm production in grazing hadronic collisions. This can be controlled by requiring that one nucleus (the photon emitter) remain intact, and that it be surrounded by a particle-free rapidity gap.

2.1.5.2 Meson Spectroscopy

Photonuclear interactions are a prolific source of vector mesons. At design luminosity, the exclusive ρ^0 production rate with gold beams is 120 Hz. Although the ground state ρ^0, ω, and ϕ mesons are well understood, their excited states are not. For example, the particle data book points out that the $\rho(1450)$ and $\rho(1700)$ may be 1 particle or 2. Data from STAR can resolve this question. If they are two particles, they will likely have different absorption cross sections, and consequently, the STAR mass spectrum from γ-A interactions will have a different shape from studies at e^+e^- colliders. These excited states have production rates ~ 1% of the ground states, and decay to a handful of particles. These studies require a complete calorimeter (for good photon detection), improved triggers and additional data collection.

2.1.5.3 Interferometry

The symmetric geometry in heavy ion collisions allows for some interesting tests of quantum mechanics. STAR has already observed the interference between the reaction when nucleus 1 emitts a photon which scatters from nucleus 2, emerging as a vector meson, and the reverse reaction. This process requires a non-local wave function which retains amplitudes for all possible particle decays even after the decay occurs. More complex systems, such as multiple ρ^0 exhibit more complex and interesting quantum interactions. Vector mesons are bosons so stimulated production of vector mesons should occur, perhaps followed by stimulated decay to specific final states. The two ρ^0 share a common polarization (via the common impact parameter vector), so angular correlations should be visible, perhaps allowing Bell's inequality-like tests. Because of the strong fields, multiple, independent vector meson production is common. In grazing collisions, the production probability is ~1% for $1\rho^0$ and ~$1\%^2/2$ for $2\rho^0$. The cross section for 2 ρ^0 production is 720 μb, or 150,000 in 2004. Other vector meson pairs, like ρ^0 and J/Ψ have smaller cross sections, requiring higher luminosities and longer runs. Both identical ($\rho^0\rho^0$) and non-identical pairs are of interest to map out the correlation space. This study requires improved triggers and additional data.

2.1.5.4 Electrodynamics in Strong Fields

The usual picture of two-photon interactions is that each beam particle emits a photon, and the photons collide. Since the coupling constant is $Z\alpha$ ~0.6 at RHIC, this picture may fail. There has been an extensive theoretical effort to study e^+e^- pair production in UPCs at RHIC; these studies have found relatively small changes in the total cross section. STAR preliminary results support these calculations, finding cross sections close to the lowest-order prediction. However, the additional photons are likely to make their presence felt in other ways, by changing the angular distributions, and in the production of multiple pairs. This study requires high luminosity, long running periods and electron identification at low and moderate p_T – the TOF system will be useful for this. To study pairs at low masses, it will be necessary to collect data with the STAR magnet at a reduced setting at either half or quarter field.

2.1.6 Diffractive Proton-Proton Physics

With the addition of Roman Pots to the STAR detector, single and double diffractive *pp* interactions, in which one or both protons emerge intact from the collision can be studied. These interactions are characterized by rapidity gaps - regions of phase space containing no final state particles. In these collisions both interacting protons loose a small fraction of their initial energy, up to 5 - 10%. This lost energy goes into the production at mid rapidity of a diffractive system with masses up to 50 GeV.

Since the scattering angles of the outgoing protons are very small (typically less than 10 mrad) they remain inside the beam pipe but can be detected with detectors inserted into the beam pipe close to the beam, the so called Roman Pots (RP). Combining this well established technique with the existing STAR detectors provides unique physics opportunities.

Diffractive interactions are believed to be mediated by the exchange of Pomerons, color singlet objects with the same quantum numbers as the vacuum. Of particular interest are double diffractive events. The cross section for double Pomeron exchange is estimated to be around 200 microbarn. About 30% of these events are resonant and non-resonant $\pi^+\pi^-$ pairs. Even at a low luminosity (1 pb^{-1} / day), very large yields are expected. The expected yield drops quickly however as a function of increasing mass of the central system as well as with the transverse momentum exchanged between the two protons.

Since Pomerons are believed to be mainly composed of gluons, the collision of two Pomerons provide a gluon rich environment which is ideal for the formation of glueballs and hybrid mesons. The center-of-mass (cm) energy in STAR is up to 25 times higher than previous experiments which have studied meson spectroscopy. The higher cm energy will allow STAR to access higher mass states, well above the charmonium threshold, as well as higher spin states, of which the tensor glueball with $J^{PC} = 2^{++}$ is the prime candidate. Furthermore, the production characteristics of mesons created in double Pomeron collisions, can be compared to g-g and g-Pomeron interactions in Heavy Ion Ultra Peripheral Collisions.

Hard diffraction is characterized by a central system of high mass decaying into 2 high p_T jets as well as the diffractive production of heavy particles including $W^{\pm}$. The study of hard diffraction, characterized by the simultaneous presence of hard and soft scales, can help elucidate the transition between soft and hard interactions, the rapidity gap survival probability, factorization, the Pomeron structure, etc.. In the case of double diffractive di-jet production, acceptance for jets with $|\eta| < 2$ is required with no particles produced at higher rapidity except for the two outgoing protons. These requirements are well matched to STAR's acceptance and trigger capabilities.

One key feature of RHIC (and STAR) is the ability to perform studies with polarized proton beams. This may allow, for the first time, studies of polarized hard diffraction, as well as of spin dependencies in central production of mesons. At present there is not much guidance from theory on possible spin dependence in diffractive processes. Observable spin effects, however, seem likely.

This physics program can run concurrently with other *pp* running (i.e. small β^* and high luminosity) as long as larger values of the four momentum transfer t ($|t| > 0.05$ GeV^2 at $\sqrt{s}$ of 500 GeV) are considered. These values of $|t|$ correspond to transverse momenta p_T of the outgoing protons > 250 MeV/c.

Detailed design of the required detectors is underway. A brief description of the likely configuration is given in section 3.3.9.2

2.2 STAR Spin Program

During the period 2004-2009, the major goal of the STAR spin program is a comprehensive study of the proton's spin structure using polarized proton collisions. The centerpiece of this program is the delineation of gluon contributions to the proton spin. It is already known that gluons contribute at least half of a proton's momentum; do they also make a major contribution to the spin? Polarized deep inelastic lepton scattering (DIS) experiments have offered indirect hints of a possible sizable contribution from gluons, but it is impractical to make polarized DIS measurements over a suitably broad kinematic range, with sufficiently good statistical precision, to cleanly determine the gluon helicity preference as a function of Bjorken x [$\Delta G(x)$], as has been done from DIS for the unpolarized gluon distribution. Direct measurements of $\Delta G(x)$, and constraints on its integral ΔG (the net contribution to the proton's spin), from polarized proton collisions at RHIC are therefore widely anticipated to fill in the next crucial piece of the proton spin puzzle.

A second major part of the STAR spin program is determination of the flavor-dependence of sea antiquark polarizations in a polarized proton, $\Delta\bar{u}(x) - \Delta\bar{d}(x)$. In light of the sizable *un*polarized flavor asymmetry in the sea revealed by Fermilab experiment E866[49], a measurement of the polarized flavor asymmetry will elucidate the interplay between perturbative (gluon splitting) *vs.* non-perturbative (pseudoscalar meson) production mechanisms responsible for the quark-antiquark sea. An important role for the latter mechanism is needed to account for the E866 unpolarized results[49]. However, antiquarks produced as part of spin 0 mesons (associated with chiral symmetry breaking) should have no spin orientation preference, while those from gluon splitting to quark-antiquark pairs may well be polarized, so that the polarized and unpolarized flavor asymmetries provide complementary sensitivity to the different mechanisms. Indeed, chiral quark soliton models that include both types of mechanism predict, on general grounds based on a $1/N_c$ expansion approach to non-perturbative QCD, that the polarized flavor asymmetry should be substantially larger (*i.e.,* lower-order in $1/N_c$) than the already sizable unpolarized flavor asymmetry[50]. In particular, these models give $\Delta\bar{u}$ and $\Delta\bar{d}$ both large, but of opposite sign, consistent with the small flavor-averaged polarization suggested by semi-inclusive DIS experiments[51]. Recent controversial results from the HERMES experiment at DESY suggest small polarization for **both** anti-up and anti-down quarks[52], in apparent contradiction to predictions based on $1/N_c$ expansions. The production of $W^{\pm}$ bosons in polarized pp collisions at RHIC offers[53] separate but equal access to $\Delta\bar{u}$ and to $\Delta\bar{d}$, via single-spin parity-violating longitudinal asymmetries. By contrast in the semi-inclusive DIS measurements performed at HERMES unraveling these quantities depends crucially on an accurate knowledge of the flavor-dependence of quark fragmentation functions and the sensitivity to anti-up quarks is greater by a factor of four (charge squared) than that to anti-down. The $W^{\pm}$ production program at STAR will receive special emphasis below because it drives one of the proposed detector upgrades for the near future.

STAR also anticipates a program of measurements that will be sensitive tope functions in the proton, *i.e.,* to the probabilities that quarks have a transverse spin orientation preference in a transversely polarized proton. In contrast to helicity preferences, where QCD couples gluon to (flavor-singlet) quark distributions in a complex way, the gluons do not contribute to transversity. Thus transversity measurements can reveal a purely quark-like property, whose integral can be compared directly to a proton property (tensor charge) calculable in lattice QCD approaches[54]. The difference between quark helicity and transversity preferences arises purely from relativistic effects in the proton's wave function. Measurements are complicated by the fact that the transversity is a chiral-odd property so observation of a transverse spin preference for quarks is equivalent to providing a mechanism for quark helicity-flip. Since QCD is a chirally symmetric theory, allowed probes always involve the product of transversity with a second chiral-odd factor, which is not known *a priori*. Because of this complication, determination of transversity usually involves multiple approaches and complementary measurements at different facilities.

Beyond 2009, the STAR spin program is less well defined, and will depend strongly on the outcome of the spin structure measurements discussed above, as well as those at other facilities. However, it is anticipated that studies of jet production at large mass scales in polarized proton collisions will play a central role. These studies will require the envisioned increase in RHIC capability as well as the planned STAR detector upgrades. In hard parton-parton collisions at p_T >10 GeV/c, the chiral symmetry of QCD generally predicts vanishingly small single-spin transverse asymmetries. A possible exception arises in the production of heavy- (*e.g.* *b*-) quark jets, where the mass-dependent terms in the QCD Lagrangian provide an explicit chiral symmetry breaking mechanism that can become appreciable when the ratio of quark mass to center-of-mass energy becomes appreciable. It would therefore be interesting to see if measurement of transverse asymmetries for *b*-quark jets can reveal these expected effects from the mass-dependent terms. If the determination of transversity is not yet settled on this time scale, and polarized pp collision luminosities can be improved, measurement of two-spin transverse asymmetries (A_{TT}) in dijet production dominated by quark-quark scattering (requiring very high p_T) may become important, because in this case the two chiral-odd factors involved are the same, *i.e.*, the measurement would be sensitive to the quark transversity squared. In a more speculative vein, the measurement of parity-violating asymmetries in quark-quark scattering dijet production at p_T ~ 50-100 GeV/c is capable of revealing (over and above the expected effects from interference between gluon and Z^0 exchange) the existence of new short-range interactions[55]. If such interactions are already revealed by LHC experiments on this time scale, polarization measurements would still be very interesting, because differences between purely longitudinal and longitudinal-transverse two-spin parity-violating asymmetries would be sensitive to the chiral structure of these new interactions.

Measurements of jets or dijets at very high p_T would require substantial luminosity and/or energy increases for RHIC pp collisions. Another type of experiment that would also benefit from such improvements involves coincidence measurements with $W^{\pm}$ production. For example, it has been suggested that the coincident detection of a spectator neutron in hard electromagnetic processes (DIS or Drell-Yan dilepton production) on a proton may provide a unique way to measure structure functions in the pion[56], an important goal given the pion's critical role as the Goldstone boson associated with spontaneous chiral symmetry breaking. How valid is the underlying assumption that the neutron coincidence implies that one has caught the proton in its intrinsic $n\pi^+$ configuration? One can check this by examining W^+ coincidences with a forward high-energy neutron: if the process indeed arises from interaction with a positive (virtual) pion, then the corresponding parity-violating single-spin asymmetry should reveal zero polarization for the struck anti-down quark.

In the subsections below, we provide more detail on the implications of the physics program outlined above for RHIC pp luminosities and for the STAR detector, and specify some of the open questions that must be answered to ensure feasibility.

2.2.1 Gluon Polarization in the Proton

A number of reaction channels in polarized pp collisions are, in principle, sensitive to gluon polarization in a polarized proton. The primary channels STAR will emphasize are direct photon production, $p+p \rightarrow \gamma + \text{jet} + X$, and inclusive jet and dijet production at moderately high p_T (> 5 GeV/c). The former is dominated at the partonic level by quark-gluon Compton scattering, while the latter has significant contributions from quark-gluon, gluon-gluon and quark-quark scattering. In each case, STAR will measure the two-spin longitudinal asymmetry A_{LL} as a function of p_T and η, providing sensitivity to $\Delta G(x)$ (see simulations in Figure 18). Of special interest are the coincidence measurements where both detected partonic products (photon+jet or jet+jet) are directed toward forward pseudorapidity, sampling asymmetric parton collisions in which a highly polarized quark from one proton collided with a low-x gluon from the other. Measurements sensitive to low x_{gluon} are critical for constraining the integrated gluon contribution to proton spin. Dijet measurements where the two jets both have high p_T and a large pseudorapidity gap between them are also of interest, because they preferentially sample quark-quark scattering, and thereby allow extraction of (valence) quark polarizations to be compared with results from polarized DIS.

These measurements will be most efficient in STAR after completion of the ongoing Barrel and Endcap Electromagnetic Calorimeter upgrades, anticipated to occur before the 2005 RHIC run. Access to the broadest possible range in x_{gluon} requires measurements at both $\sqrt{s}$ = 200 and 500 GeV. Running at two energies provides an additional extremely valuable crosscheck on the pQCD interpretation of the results, because the same x_{gluon} values can be probed at two substantially different momentum transfer scales. In practice, this x_{gluon} overlap requires detection of photons from 500 GeV collisions at p_T > 20 GeV/c, a range in which the calorimeter preshower layer readout for both the barrel and the endcap will be needed to aid in γ/π^0 discrimination. Extensive simulations (see Figure 18), especially for the photon+jet channel, assuming integrated luminosities of 320 pb^{-1} at 200 GeV and 800 pb^{-1} at 500 GeV and beam polarizations of 70% have demonstrated that gluon polarizations can be measured to at least the ±0.05 level in each of a significant number of bins spanning $0.01 < x_{\text{gluon}} < 0.30$, constraining the integral gluon contribution to the proton spin to a (statistical plus systematic) uncertainty of ~±0.5 (a significant improvement over present constraints from polarized DIS). At design luminosities and polarizations, these measurements would require a 10-week run at each of the two energies. However, the measurements are not feasible without dramatic improvements in both beam polarization and luminosity from the polarized collision performance demonstrated to date at RHIC. Assuming rapid improvements over the next two years, a reasonable plan would involve 200 GeV measurements in 2006-7 and 500 GeV measurements in 2008-9.

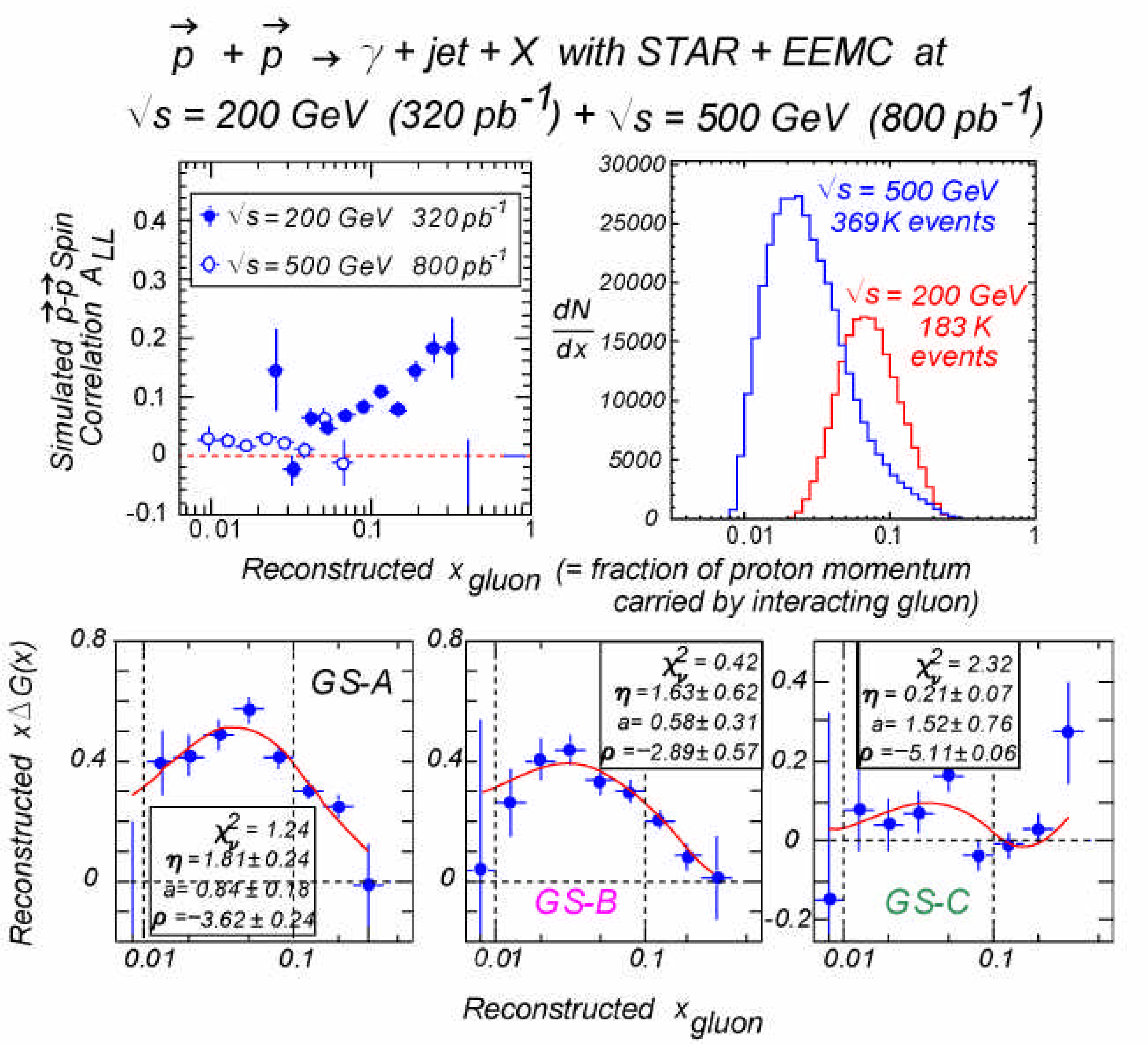

Figure 18 PYTHIA simulations of STAR's sensitivity to the gluon helicity preference $\Delta G(x)$ in the photon-jet channel, assuming full barrel and endcap EMC coverage and measurements at both 200 and 500 GeV. The upper frames illustrate simulations of the two-spin longitudinal asymmetry to be measured and the yield of events as a function of the gluon's Bjorken x-value, reconstructed in a simplified leading-order pQCD analysis (see ref. 57), for one choice of parton distribution functions (Gehrmann-Stirling set A[58]). The lower frames illustrate the values of $x\Delta G(x)$ reconstructed in the LO analysis for three different choices of input gluon helicity distribution (Gehrmann-Stirling sets A, B and C[58]), together with fits to the simulated results using a conventional functional form. Error bars are statistical only. The simulations illustrate the x-range and statistical sensitivity anticipated from the data.

2.2.2 Flavor-Dependence of Sea Antiquark Polarizations

The $W^{\pm}$ detection needed for measurements of anti-up vs. anti-down sea quark polarizations is done in STAR by measuring the transverse energy of the daughter positron or electron in the barrel or endcap EMC. This program involves measurement of the *single*-spin longitudinal (parity-violating) asymmetry A_L sensitive to the independent flip of each beam's spin orientation, as a function of p_T and η of the daughter electron/positron. These two analyzing powers (each averaging over the helicities of one proton beam or the other) for each charge sign of the detected lepton permit extraction of the polarization of a quark (u for W^+, d for W^-) in one proton and of an antiquark ($\bar{d}$ for W^+, $\bar{u}$ for W^-) in the other. The simulation results shown in Figure 19 (see also[59]) indicate the probability that it is the proton beam heading toward positive pseudorapidity (i.e., toward the endcap EMC) that supplies the quark, as opposed to the antiquark, so that the asymmetry measured with respect to helicity flip of this beam provides a measure of the quark's polarization. This probability shows opposite trends as a function of pseudorapidity for W^+ *vs*. W^-, as a result of CP conservation in the decay, because the daughter positron in the first case is emitted preferentially parallel to the W spin (hence, opposite the momentum of the left-handed W), while the daughter electron in the second case is emitted preferentially opposite the W spin (parallel to its momentum). In both cases, however, the quark-antiquark distinction is cleanest when the daughter lepton is detected in the endcap EMC, because the kinematics then favor asymmetric parton collisions involving a high-x quark and a low-x antiquark. Significant W-production yields can be obtained at RHIC only at the upper end of the energy range, $\sqrt{s}$ = 500 GeV. An integrated luminosity of 800 pb^{-1} will permit detection of about 57K W^+ and 14K W^-, sufficient to measure antiquark polarizations typically to $\pm$ (0.03 - 0.05) in $\eta(e^{\pm})$ bins of width 0.30, *i.e.*, to provide a stringent test of models of the sea quark polarizations.

There are two crucial aspects of the detection needs for this program: electron/hadron discrimination and electron/positron charge determination at p_T up to 40 GeV/c. The former is needed along with isolation cuts and dijet rejection cuts to pull the W production signal out from a much larger background of high-p_T charged hadrons that begin to shower in the EMC's. It requires preshower readout to be available for both barrel and endcap calorimeters. In the case of the endcap, the addition of postshower detector readout (a modest upgrade) is quite useful as well, since the TPC p_T resolution deteriorates rapidly in this region, compromising *e/h* discrimination via comparison of p_T to E_T. The TPC resolution problems in this region are most critical for discriminating electrons from positrons, which becomes quite difficult beyond $\eta\approx1.4$ with the present tracking. As sign discrimination is crucial for extracting the antiquark flavor-dependence of greatest physics interest, this drives STAR's proposal to add improved forward tracking in front of the endcap calorimeter. For example, e^+ vs. e^- discrimination could be provided over the entire endcap region and up to 40 GeV/c with >99% confidence via the addition of two space points measured at longitudinal distances of roughly 1 m and 2.5 m from STAR's center, with spatial resolutions no worse than σ=100 μm transverse to the beam direction. These points would be provided by the outer barrel layer of an intermediate tracker, just inside the TPC inner radius, and a tracking chamber just before the endcap. The beam crossing trajectory determined from the vertices of other events measured in the same fill would provide a third high-resolution transverse space point for charge sign determination, while the endcap calorimeter's shower-maximum detector (SMD) would provide a fourth, lower-resolution (~1 mm) measured space point to confirm that the two forward tracking points indeed lie on a single high-p_T track. The same sort of tracking resolution would simultaneously provide a substantial improvement in *e/h* discrimination. Simulations of the $W^{\pm}$ signal cleanliness and sign discrimination as a function of configuration of forward tracking devices are under way. The *W* production measurements would best be made after installation of improved forward tracking, in the 2008-9 time period. To make space for an endcap tracker, the present TPC readout boards will have to be replaced with significantly more compact ones, but this will happen naturally as part of the FEE upgrade to improve STAR's DAQ rate capability. *W* production can run concurrently with 500 GeV direct photon measurements to determine the gluon polarization.

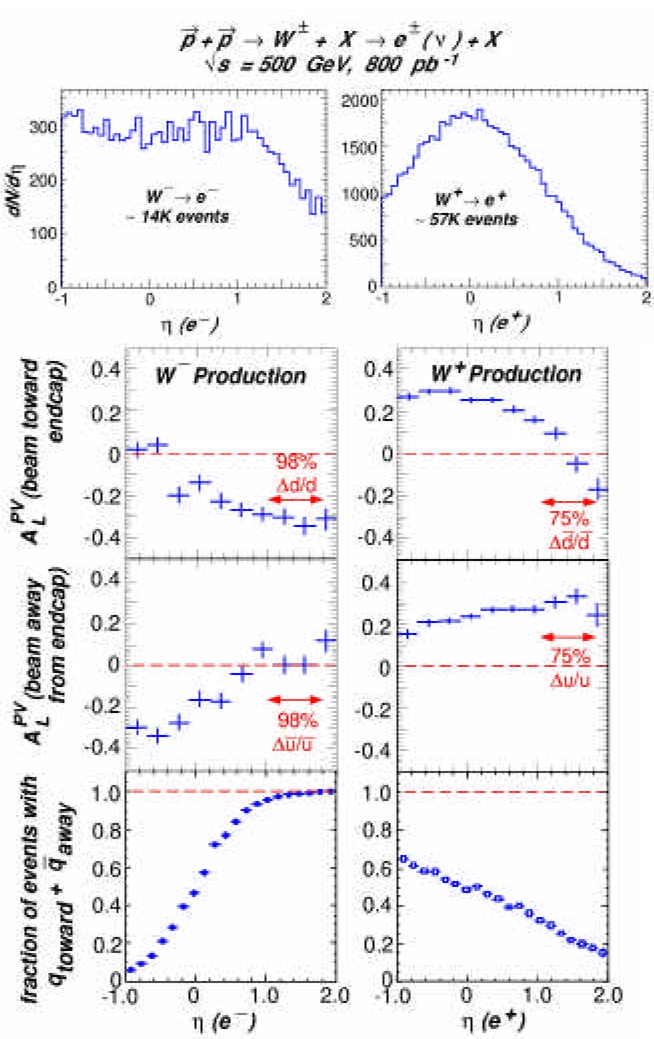

Figure 19. PYTHIA simulations of the yield (upper frames) and the parity-violating single-spin helicity asymmetries (middle frames) anticipated for W^- (left frames) and W^+ (right frames) production in STAR at 500 GeV, as a function of the pseudorapidity of the detected daughter electron or positron, using one particular choice of helicity distributions for anti-up and anti-down quarks. Four independent asymmetries will be measured – two each for W^+ and for W^-, in each case averaging over the spin orientation of one of the two beams. The upper (lower) middle frames show the sensitivity to helicity flip of the proton beam headed toward (away from) the endcap EMC, while the lowest frames show the fraction of events where the colliding quark comes from the former beam. The averages of these fractions over the endcap region are summarized by the percentages specified in the middle four frames. The distinction is cleanest, so that measured asymmetries can be interpreted most directly in terms of quark vs. anti-quark helicity preferences, in the endcap region, especially for W^-. Error bars are statistical only, and do not include effects of subtracting charged hadron background that may remain after application of all hadron suppression cuts.

2.2.3 Quark Transversity in the Proton

Transversity measures, as a function of Bjorken x, the difference in probability of finding quarks with spin orientation parallel *vs.* anti-parallel to the spin of a *transversely* polarized proton. Such a transverse spin preference can occur at leading twist in QCD, just as can a helicity preference, but it represents a chiral-odd property of the proton, equivalent to replacing a left-handed quark by a right-handed quark, or vice-versa[60]. To probe transversity, one needs a process involving a second chiral-odd factor, so that overall chirality is preserved. In the simplest case, the second chiral-odd factor would be another transversity: for example, the product of two quark transversities sampled in transverse two-spin asymmetries for quark-quark-dominated dijet production, or the product of a quark with an antiquark transversity sampled in the same sort of asymmetry for Drell-Yan processes. However, measurements at interesting sensitivity levels for either of these processes requires significant enhancements beyond presently envisioned pp luminosities at RHIC (the dijet case is discussed further in the subsequent subsection). Alternatively, the second chiral-odd factor can be provided by a more subtle transverse spin-dependence in the initial or final state. Examples include twist-3 quark-gluon correlations[61] inside the incident polarized proton or spin-dependent transverse asymmetries in final-state (polarized) quark fragmentation functions. The latter can show up as a preference for hadron emission to one side of the plane formed by the quark spin and the jet axis, manifested either for single hadrons (the so-called Collins effect[62]) or for pairs of unlike hadrons undergoing a final-state interaction where two orbital states interfere (interference fragmentation functions[63]).

Inclusive single-spin transverse asymmetries A_N, such as that already measured in STAR for π^0 production at large pseudorapidity[64], are sensitive to transversity in the proton, but because they may receive non-negligible contributions from several of the above examples of (poorly known) second chiral-odd factors, as well as from a possible proton-spin-dependent "sidedness" to the transverse quark momentum distribution (so-called Sivers effect[65]) in the incident proton, it is difficult to determine transversity quantitatively from such inclusive measurements. Thus, STAR's transversity program in the shorter term (until 2009) will focus on measuring transverse spin asymmetries associated with either Collins or interference fragmentation functions for outgoing jets. This program exploits STAR's large acceptance and full jet reconstruction capabilities. In the former case, one still measures A_N for individual moderate-to-high p_T hadrons, but now comparing results for jet fragments to one side *vs.* the other side of the reconstructed jet axis. In the latter case, one searches for an asymmetry in $\pi^+\pi^-$ pair production, dependent on the triple proton-spin-pion-momentum correlation $\boldsymbol{s}_p \bullet (\boldsymbol{p}_{p-} \times \boldsymbol{p}_{p+})$, specifically for pion pairs with invariant mass in the immediate vicinity of the ρ. The localization of the invariant mass is desirable to take advantage of a known interference effect in $\pi\pi$ scattering phase shifts, which would give rise to a change in sign of the interference fragmentation function as one crosses the ρ mass[63]. The asymmetry would be measured as a function of both p_T of the jet and the fraction z of the full jet momentum carried by the detected charged pion pair.

The measurement of Collins asymmetries in association with forward pion production, where STAR results have already demonstrated sizable inclusive transverse analyzing powers[64], would benefit from the addition of forward hadron calorimetry to aid in jet reconstruction. Reconstruction of the forward jet energy in $p{\uparrow}p$ collisions at RHIC also would more directly establish the Bjorken x dependence of the transversity structure function by eliminating the momentum smearing associated with its fragmentation into a single hadron. The measurement of interference fragmentation function asymmetries would benefit from the proposed TOF upgrade for STAR, which will extend pion particle identification capabilities to a momentum range of interest for jet fragments. Triggering could be accomplished by detection of an away-side jet or high-p_T π^0 in the barrel or endcap EMC. The anticipated transverse spin asymmetries are of order a few percent, and the probability for jet fragmentation to ρ-mesons is sizable, so that meaningful measurements could be performed with present design pp luminosities in a transverse spin run of modest duration, interspersed with the predominant longitudinal spin running during the 2007-9 time period, after the TOF upgrade is installed.

Quantitative determination of transversity from measurements such as these will rely on independent calibrations of the Collins and interference fragmentation functions, in complementary experiments at other facilities. For this purpose, dijet production events in e^+e^- collisions are particularly suitable because the spins of the quark and antiquark parenting the two jets are completely correlated. Thus the fragmentation functions can be determined from correlations of asymmetries between the two jets. STAR (and PHENIX) collaborators participating in the BELLE experiment[66] at the KEK B-factory hope to have results for these fragmentation functions by the time RHIC transversity studies would be performed.

2.2.4 Jet Production at High Mass Scales

The large acceptance of STAR makes it suitable for physics investigations of spin effects in jet production. Early STAR spin measurements will concentrate on longitudinal two-spin asymmetries for inclusive jets at moderate p_T of 5-20 GeV/c, where one has significant sensitivity to the gluon polarization in the proton. However, other searches for more subtle spin effects for higher p_T jets, or for heavy-flavor tagged jets, will require some improvement over design luminosities to reach interesting sensitivity limits. In the spin physics introductory section above, we highlighted three potentially interesting measurements of this sort: (1) a measurement of single-spin transverse asymmetries A_N for b-quark jets, to search for effects of the quark-mass-dependent terms in the QCD Lagrangian; (2) a measurement of two-spin transverse asymmetries A_{NN} for dijet events dominated by the hard scattering of two valence quarks, to determine quark transversity in the $x > 0.2$ region; (3) a measurement of two-spin parity-violating longitudinal asymmetries for inclusive jet production at $p_T > 50$ GeV/c, to search for ultra-short-range parity-violating interactions beyond the Standard Model[55]. The first two of these measurements could be performed simultaneously with transversely polarized beams at $\sqrt{s}$ = 200 GeV, with interesting sensitivities requiring accumulation of samples of at least ~10^5 tagged b-quark jets and ~10^6 dijet events at $p_T > 20$ GeV/c, respectively. Attainment of these yields would require integrated pp luminosities in excess of 500 pb^{-1}, and hence a pp luminosity improvement over the "enhanced" design specification by a factor of 2-4. At these modestly increased luminosities, the STAR pp program could probably still run effectively with the existing TPC. The proposed micro-vertex detector upgrade would be used to aid in tagging b-quark jets.

The Standard Model predicts two-spin parity-violating asymmetries A_{LL}^{PV} for hard jet production in pp collisions approaching 0.02 at $p_T \approx 100$ GeV/c, arising from the interference of Z^0- with gluon-exchange between quarks[55]. The momentum transfer range of interest here is set by the Z^0 mass, and corresponds at RHIC energies to Bjorken x-values of the interacting quarks where the quark distribution functions and helicity preferences inside the proton are well known from deep inelastic scattering results. Hence, significant deviations from the Standard Model predictions may well reflect new physics, such as contact interactions associated with quark substructure (see Figure 20). Polarization measurements can compete in sensitivity to such new interactions with cross section measurements made at much higher c.m. energies, besides having the potential to reveal crucial spin-dependent features of the interaction not accessible in cross section measurements. For example, a STAR spin measurement could push existing limits on the mass scale associated with such contact interactions up by a factor ~2 if A_{LL}^{PV} could be measured to ~ ±0.002 at 100 GeV/c. Achieving such statistical precision would require a very substantial increase in polarized pp luminosities at RHIC. For example, Murata[67] has estimated that this goal could be achieved with an integrated luminosity approaching 10^4 pb^{-1} and an energy upgrade to $\sqrt{s}$ = 650 GeV (the energy upgrade providing the equivalent of an additional factor of 2 luminosity improvement). Measurements at that level could be conceived only in the next decade, if it were possible to provide an order of magnitude enhancement over design pp luminosities. At that luminosity level, the STAR TPC would certainly have to be replaced with a faster detector to maintain manageable pileup of tracks from different beam crossings. The STAR EMC granularities are such that the anticipated multiple events per beam crossing would still not produce unreasonable occupancies in the calorimeter. The higher luminosities would also permit acquisition of a sizable sample of Z^0 production events, of interest not only for their intrinsic physics sensitivity to sea antiquark polarizations, but also for giving suitable high-energy calibration points on the calorimeters that would be used to set the jet energy scale. Simulations are needed to determine if the jet energy could be measured adequately without addition of large-coverage hadron calorimetry to STAR.

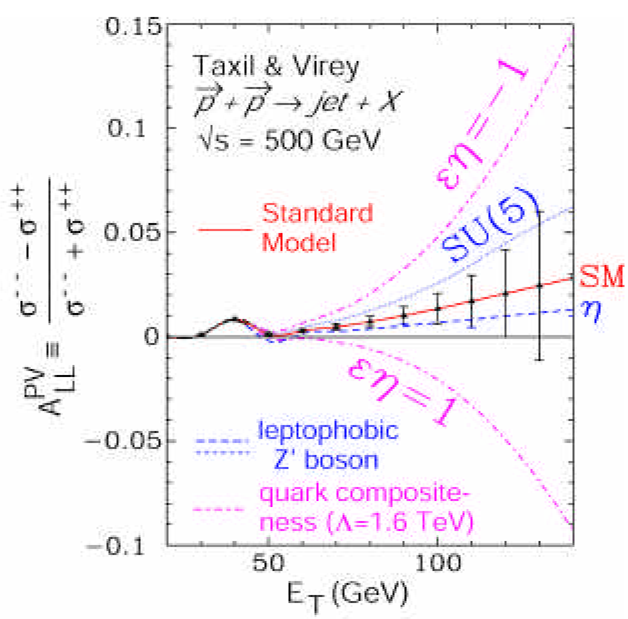

Figure 20. Parity-violating asymmetries predicted[55] in the Standard Model and for selected physics beyond the Standard Model, for hard jet production at RHIC energies. The error bars reflect the statistical precision achievable with a 100% acceptance × efficiency detector in one year of running at $\sqrt{s}$ = 500 GeV [55]. Substantial polarized pp luminosity improvements, and a possible modest energy upgrade, would be needed to attain sensitivity to quark compositeness mass scales well beyond present limits from Tevatron experiments.

2.2.5 Probing the Proton's "Inner Pion"

If the W production experiments at RHIC reveal substantial polarizations for the anti-up and anti-down quarks in the proton sea, it will become interesting to probe the chiral structure of the sea more deeply. A particularly revealing measurement would be that of parity-violating single-spin helicity asymmetries A_L for the process $\vec{p} + \vec{p} \rightarrow W^+ + n + X$, with a positron from the W decay detected in coincidence with a forward high-energy neutron in one of STAR's Zero-

Degree Calorimeters (ZDC). It is anticipated that detection of a neutron carrying a majority of the proton's momentum would signal that one of the interacting protons has fragmented into the detected neutron and a p^+ on which the W production occurred. Indeed, analogous measurements made by the H1 collaboration[56] on semi-inclusive deep inelastic electron scattering from the proton, involving a spectator neutron tag, have been interpreted as measuring pion structure functions. If this expectation is valid, then one would expect the value of A_L measured with respect to helicity-flip of the proton beam in the detected neutron direction to be zero, since the anti-down quark provided by that beam was contained in a spin-zero meson. Deviations from this expectation would suggest that the proton wave function configuration probed is more complicated than np^+. On the other hand, the helicity asymmetry with respect to the other proton beam would be large, since the up quarks at sizable Bjorken x in a polarized proton have a substantial polarization.

Based on calculations involving the pNN coupling and form factor, the probability for detecting a neutron carrying at least 60% of the proton's momentum in one of the ZDC's is expected to reduce the coincidence rate by about a factor of 20, in comparison with the singles rate for W^+ detection[68]. Thus, in the anticipated long run at $\sqrt{s}$ = 500 GeV focusing on inclusive W production, one might already detect a few thousand appropriate coincidence events, enough to judge the integrated luminosity needed for a meaningful measurement of asymmetries for W-n coincidences. The coincidence measurement is one that places similar demands on beam energy and luminosity to the jet parity violation experiment discussed in the preceding subsection, so that these two measurements could be made simultaneously if suitable pp luminosity and/or energy upgrades can be accomplished in the next decade. If relevant conditions are attained, one could consider extending this type of measurement as well to the strange sector (possible ΛK^+ configuration) by detection of decay daughters from a forward high energy Λ in a contemplated STAR forward hadron calorimeter.

3 Star Upgrade Plans

3.1 Overview

The physics program outlined in the sections above indicates several major directions for upgrading the STAR detector to meet the challenges of making higher precision measurements, measurements using rare probes, high statistics measurements, and high momentum measurements. These include extending the momentum reach of the particle identification by installing full barrel coverage time-of-flight detectors, building a microvertex detection capable of resolving charmed particle decays, upgrading the front end electronics and data acquisition system, improvements to the trigger by incorporating new fast detectors, improved momentum resolution, and ultimately, replacement of the STAR TPC with a tracker which will provide similar functionality at high luminosity. Also currently under active discussion in STAR are improved coverage in the forward region with hadron calorimetry ($2.4<\eta<4.0$) and Roman pots (η~6.5). We envision a staged series of upgrades which will allow optimum exploitation of the RHIC improvements in luminosity up to the RHIC II era, and also poise STAR for the high luminosity RHIC II operation. Figure 21 shows a proposed time for the major upgrades. A proposal has been submitted to DOE for the barrel time-of-flight detector. A proposal is in preparation for a pixel micro-vertex detector which will allow detection of charmed particle decays. We give a brief description below of the ongoing upgrades in STAR followed by a description of each of the planned upgrades.

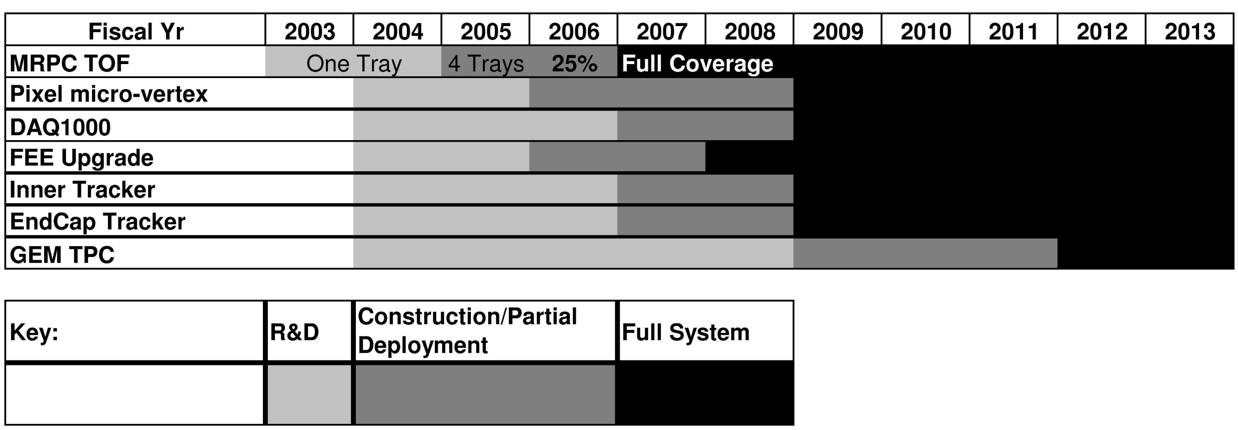

Figure 21 Proposed timeline for STAR detector upgrades.

3.2 Ongoing Upgrades

3.2.1 Barrel Electromagnetic Calorimeter, Endcap Electromagnetic Calorimeter

The STAR electromagnetic calorimeters are vital to many of the physics measurements in both the heavy ion and polarized proton programs. In the heavy ion program, they are required for measurement and triggering for inclusive π^o spectra to very high p_T, studies of away-side jet suppression vs. E_T and η, γ-tagged jet measurements, direct photon measurements at moderate to high p_T, Υ and J/Ψ yield and spectra measurements, and coherent J/Ψ and open charm photoproduction in ultra-peripheral collisions. For polarized proton measurements, the calorimeters are required for measuring A_{LL} for photon-jet coincidences and they are also vital to measurements involving W detection. For both programs, the calorimeters provide the major level 0 high p_T trigger capability for STAR.

The STAR barrel electromagnetic calorimeter (BEMC) is a lead-scintillator, tile geometry, sampling calorimeter with fiber readout covering $-1 < \eta < 1$ and $0 < \phi < 2\pi$ with 4800 segments each covering $(\Delta\eta,\Delta\phi) = (0.05,0.05)$. A preshower layer with the same segmentation allows improved e/h discrimination as well as providing γ/π^o discrimination. This layer is vital for W detection. A shower maximum layer with 36000 channels of fine grained wire chamber readout to allow separation of close showers as well as shower shape measurements for improved e/h discrimination.

The endcap electromagnetic (EEMC) calorimeter covers the west endcap of STAR just inside the magnet pole tip. It is 21 radiation lengths deep and spans $1.09<\eta<2.0$ and $0<\phi<2\pi$ with 6^o segmentation in ϕ and 12 radial segments varying from $\Delta\eta=0.057$ to 0.099 (Figure 22). It is also a sampling Pb-scintillator tile geometry detector with fiber readout and has preshower, shower maximum and post shower layers. In the endcap region, the added e/h discrimination from the post shower layer helps to compensate for the degraded E/p constraint from the poorer momentum measurement in the TPC at larger η. Both calorimeters are expected to have $15\%/\sqrt{E}$ energy resolution.

Both the endcap and barrel calorimeters are integrated into the STAR pipelined trigger architecture and can provide a variety of flexible, programmable triggers based on electromagnetic energy and topology allowing STAR to trigger on:

- High p_T in STAR.
- High energy photons allowing access to direct photons, for measuring the gluon structure functions of nuclei and for jet quenching studies
- High energy electrons for *W*'s and *Z*'s in the spin physics program
- Moderate energy electrons and di-electrons for J/ψ and upsilon in both the heavy ion and light ion programs
- Jets for measurement of the gluon structure function and its spin content and for studying jet quenching in a plasma

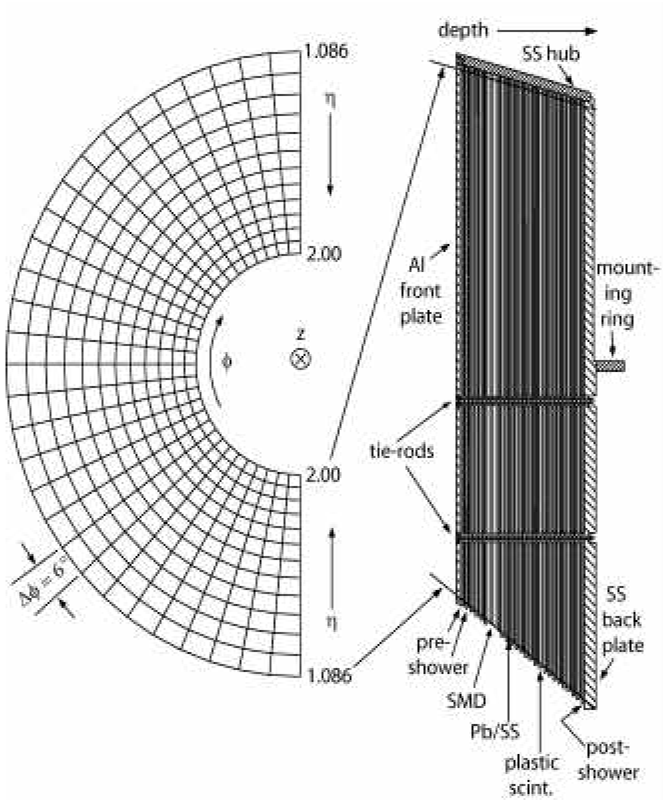

Figure 22. Endcap Electromagnetic Calorimeter, beam and cross section view. For clarity, only 1/2 of ϕ coverage is shown in beam view.

For the 2003 run, ½ of the barrel electromagnetic calorimeter and 1/3 of the end cap electromagnetic calorimeter were installed in STAR. Both of these calorimeters are expected to be complete for the FY2005 run.

3.2.2 DAQ100

Through a series of incremental improvements over the first three years of operations, the STAR Data Acquisition System has been upgraded from the initial baseline design capability of 1 central Au+Au event/second to now allow ~40 central events/sec (at 100% deadtime).

The software code as well as most parts of the hardware (collectively called "DAQ100") were already in place for the just completed d+Au run, however with the smaller event size in d+Au collisions the system was not stressed. For the next Au+Au run, where a major goal is collecting a very large sample of collisions, DAQ100 is vital.

These improvements were largely accomplished (a factor of 5) by moving the first stage of the TPC's raw data processing (the "cluster finding") into the real-time data acquisition computers so that the output of this stage contains already preprocessed (and thus compressed) data.

With this shift of data processing, every part of the system runs at the maximum achievable capacity. Further improvements will require significant hardware changes.

3.2.3 FPD

A prototype version of the Forward Pion Detector was initially installed for the FY2002 run. This detector is a group of four electromagnetic calorimeters each (above, below, left and right of the beam axis) on both the east and west sides of STAR covering $2.4<|\eta|<4$. The full detector was installed and commissioned during the FY2003 run, although part of the readout electronics was still the prototype version (shower max.). These devices are capable of identifying and measuring π^o to energies well above 60 GeV. The FPD is vital for the polarized proton running since it provides a local polarization measurement. These calorimeters provide trigger capability and allow important physics measurements. The prototype used in the first run demonstrated the capability to measure the π^o asymmetry in transversely polarized proton collisions (see Figure 12).

3.2.4 Trigger Upgrades

The STAR trigger is a fully pipelined hierarchic system with Level 0 capable of operating at the RHIC clock frequency. The ongoing upgrades consist of adding new fast detectors (barrel and endcap calorimeters, forward π^o detector), implementing Level 1 and 2 aborts required to bring these trigger levels to full functionality, and adding new algorithms at all levels.

3.2.5 Photon Multiplicity Detector.

The PMD will provide a measurement of the multiplicity and spatial distribution of photons within the pseudorapidity range 2.3–3.5 and is located behind the forward time projection chamber on the east side of the main STAR detector. The basic principle of the measurement of photon multiplicity using the PMD is similar to that of the preshower detectors used in WA93 and WA98 experiments at the CERN SPS[69,70]. It consists of highly segmented proportional counters placed behind a lead converter of suitable thickness. A photon produces an electromagnetic shower on passing through the converter which produces signals in several cells while charged hadrons usually only affect one cell. Another plane of the detector of identical dimension to the preshower part is placed in front of the lead plate and acts as a veto for charged particles. The two detector planes (veto and photon detector) each consist of more than 40,000 individual cells each isolated to prevent the spread of soft δ-rays. This very high granularity will allow the detector to perform well in the high particle densities expected in this forward region. Simulations show that the PMD will have a photon detection efficiency of about 60% and a purity of about 60%.

Commissioning work was carried out in the 2003 run and the detector is expected to be completed for the 2004 run.

3.2.6 SSD

The silicon strip detector consists of a single layer of double sided silicon in a barrel configuration that lies between the SVT and TPC. It will help link TPC tracks with the silicon vertex detector thus giving an overall improvement in efficiency for physics requiring the SVT and TPC. One ladder was installed for engineering tests in FY2003. One half of the system will be in place for the FY2004 run with completion expected for the FY2005 run.

3.3 Ten Year Upgrade Plan

3.3.1 Barrel Time-of-Flight Detector

Full coverage of the TPC outer barrel with a time of flight detector was in the STAR baseline design. Conventional scintillator-mesh dynode PMT (inside the solenoidal field) proved to be too expensive, so an R&D program to find a cost effective solution was undertaken. This program involved members of STAR working with CERN and has successfully resulted in the development of MRPC (multi-gap resistive plate) time-of-flight detectors

One tray (1/120th) of the proposed Multi-gap Resistive Plate Chamber was installed in STAR for the 2003 run (Figure 25). This tray is providing valuable experience in using this technology in STAR. The tray performed extremely well during the run and is will add to the physics output from the run. Figure 23 shows the particle identification performance of the TOFr tray in the recently completed d-Au run. Although the calibrations are still being optimized, a stop time resolution of ~ 85ps from the 72 TOFr channels in the d+Au data set was observed.

Additional PID capability arises from combining the TOF velocity measurement with the TPC dE/dx measurement. Figure 24 shows the TPC dE/dx for all tracks used in Figure 23 (top panel). The bottom panel shows the same information for those tracks with a TOF measured velocity consistent with β=1. This cut removes slow tracks so that a clean electron band (upper band) is now visible. We are actively investigating the use of this electron tag to study e^+e^- decay modes of vector mesons once the full coverage TOF is implemented. Detailed simulations as well as the data in hand should allow characterization of the background.

A proposal has been submitted to DOE for the full coverage MRPC tim-of-flight detector. This detector will extend π+K/p separation to ~3 GeV/c over nearly the full acceptance of the TPC and the barrel calorimeter. This will greatly enhance the p_T range and sensitivity for all studies of flavor-dependent phenomena, and is pivotal for many of the measurements discussed in the preceding sections.

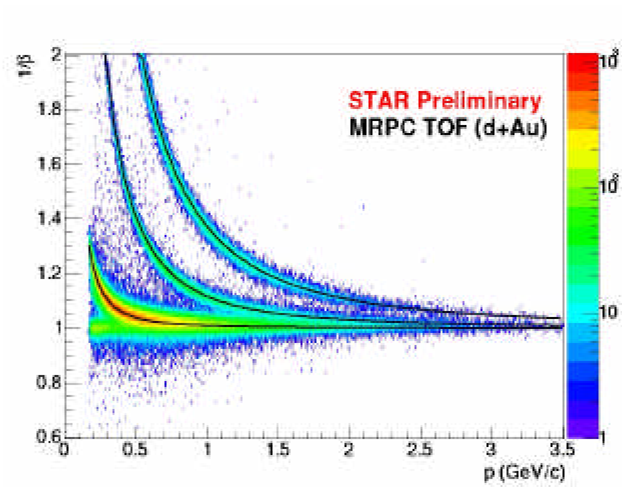

Figure 23. 1/β from TOFr vs momentum measured in the TPC from d-Au events.

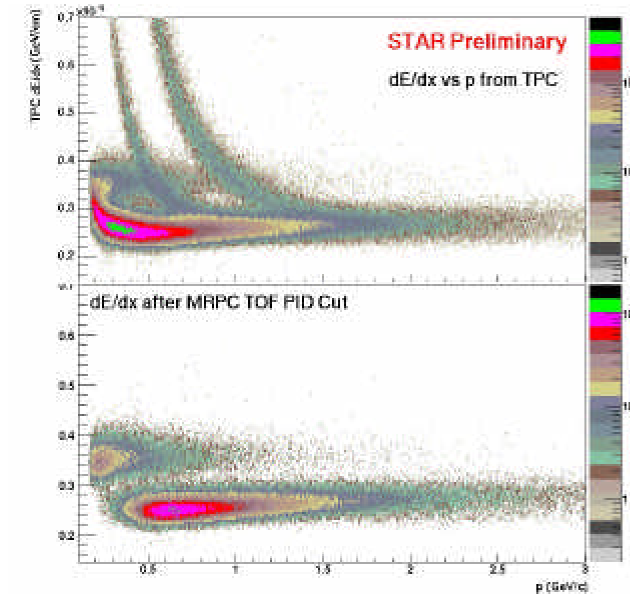

Figure 24 Top panel shows TPC dE/dx for all tracks from d-Au run. Bottom panel shows those tracks with TOF measured velocity consistent with β=1. A clear electron band (upper band) is now visible.

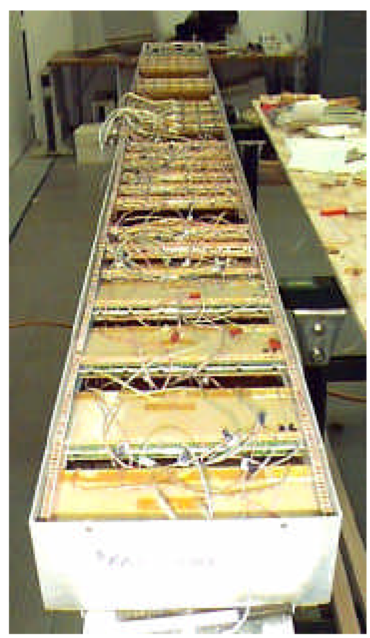

Figure 25. ToFr. Prototype MRPC time of flight tray installed in STAR for the 2003 d-Au and p-p runs. The tray, which was mounted outside the STAR TPC outer radius, covers 1/60th of the azimuth and ½ of the length along the beam line of the STAR acceptance. Each of the 32 MRPC modules visible in the tray has 6 readout channels. A total of 72 channels were instrumented with readout electronics for the 2003 run.

MRPC technology is now well established and has operated in the RHIC environment. Development is required for final design and prototyping of the readout electronics, in particular for implementation of the CERN HPTDC chip. The physics value of this detector becomes greater the sooner it is available. An effort is being made to initiate the project as a joint U.S.-

China project to begin construction of the full detector as early as FY 2005 with completion in FY 2007. Details of the detector design can be found in the STAR time of flight proposal[33].

3.3.2 Microvertex Detector

The microvertex detector will provide ~10 μm resolution for tracks near the collision point with point back accuracy of <20μm at the primary vertex. This is essential for the study of open charm and beauty and c- and b-quark jets via displaced electrons. The upgrade will be of immediate benefit to the program and should be implemented as soon as possible. The LBNL group (H. Wieman) is studying the Active Pixel Sensor (APS) technology developed at LEPSI/IReS (Figure 27). The APS devices have the great advantage that they use standard CMOS technology thus allowing incorporation of readout electronics on the detector chip. This eliminates the need for connecting every sensor element to an external readout chip. There are programs at both LEPSI/IReS and LBNL/UC Irvine to develop next generation faster APS technology for this application. The CERN/ALICE approach of using hybrid pixel devices is further along in development but has the disadvantage of requiring a lot of material in the innermost tracking region. Although the present APS devices have readout that is too slow for the full RHIC II luminosity, this is expected to improve with development effort. A phased approach is possible whereby a first-generation APS detector is installed on a fast track, and replaced later. This is an area where STAR and PHENIX have shared R&D interests. A major part of the required development is the necessary infrastructure to mount the detector with minimal material in the detector's active aperture. This includes developing low mass supports (Figure 26), a very thin beam pipe with the smallest allowed radius, and methods for assuring precision alignment. It is expected that three years of development will produce a device suitable for use in STAR.

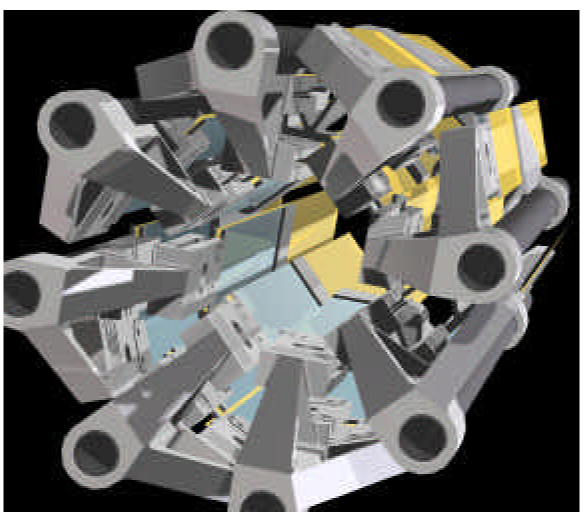

Figure 26. Possible design for support of thinned APS detectors.

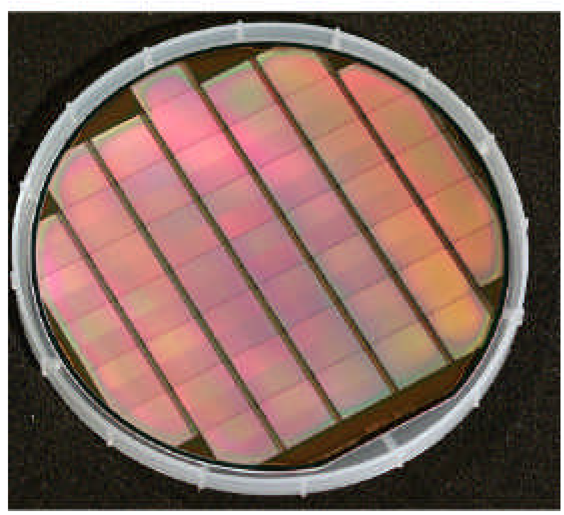

Figure 27. Full APS ladders produced on a wafer at LEPSI.

3.3.3 Intermediate Tracking

For the pixel microvertex detector to be useful, one must match the TPC tracks to hits in the pixel detector. This requires tracking detector(s) between the pixel detector and the TPC with resolution intermediate (and possibly graded) between that of the TPC and the pixels. Currently, the STAR SVT will serve that function, however, the SVT readout speed is not consistent with the proposed DAQ speed upgrade. Further, at the time of implementing the pixel detectors and the DAQ upgrades, the SVT will have been in use for 6 – 8 RHIC runs so that aging is a concern since the inevitable uncontrolled beam losses limit the useful lifetime of a solid state inner tracking detector. Design studies are being undertaken for the required intermediate tracking to match the capabilities of the pixel detector. An initial design using GEM based pad chambers just inside the TPC inner radius and silicon strip detectors between the pad chambers and the pixel detectors looks promising, however, detailed simulations remain to be done. Since the detectors being considered are “fast,” they would help resolve event pile-up in p-p running and also be compatible with expected rates in RHIC II.

The detector requirements in this region will also include coverage in the region $1<\eta<2$ to aid in the charge determination of the decay lepton from W’s produced in polarized proton collisions.

3.3.4 High-rate upgrades for Front End Electronics and Data Acquisition System

The STAR TPC electronics and data acquisition is currently limited to a processing rate of 100 events per second. Due to other constraints on the system the practical rate is equivalent to about 40 central Au+Au events/second. Improvements of the DAQ system have been implemented for RHIC Run 4 and beyond to achieve this rate which is 40 times the baseline STAR design.

Since the 100 events/sec represent a hard limit due to the hardware implementation, the TPC front end electronics would be replaced and a new data acquisition system based upon the fast "DAQ100" cluster finder code would be constructed. The goal of the new system would be a tenfold increase of rates to more than 1000 Hz. The CERN/ALICE front end TPC chip is in the final stages of development, and could be implemented in STAR for this purpose. In order to accomplish this, along with the upgrades to the DAQ electronics, a significant R&D effort must be carried out before the final system is ready. A two year R&D effort should be adequate to develop the new front end electronics. At least this much time is required for design and development of the data acquisition system to match the new front end requirements. This would mean construction could begin in ~2006, with full implementation approximately two years later.

3.3.5 Trigger

The present trigger architecture of STAR is capable of dealing with the planned luminosity upgrades for RHIC, but new, fast detectors will need to be incorporated. Examples include the barrel TOF, to replace the Central Trigger Barrel with higher granularity, and a high resolution Vertex Position Detector. Including these new systems will require redesign of some trigger boards in order to phase out chips and components that are no longer available. A significant upgrade of the Level 3 trigger will be required to take advantage of the enhanced readout and DAQ rates while maintaining a manageable recording rate. For the highest possible event recording rate which would be needed for acquiring very large data samples in the RHIC II era, it is expected that level 3 may be required to perform precision tracking so that only track data will be recorded.

3.3.6 Forward Tracking Improvement

An upgrade of the tracking in the region $1<\eta<2$ (STAR endcap region) is required for W charge sign determination. For example, a 50 GeV/c electron at a psuedorapidity of 1.4 only traverses the first (inner) 55 cm of the TPC, leaving a track with a saggitta of only 500μm. Given the track distortions in the TPC, especially those due to space charge from positive ion build up which vary with luminosity and background and can only be calibrated to a limited extent, reliably detecting the sign of such a small saggitta is not really possible using the TPC alone. To alleviate this problem requires improved tracking in the forward direction. The COMPASS experiment at CERN uses GEM multipliers in a pad-chamber geometry with crossed strip readout. With 400 μm pitch strips, they have achieved 50μm spatial resolution in two dimensions. This technique is very promising for high precision space point measurement on the STAR endcap to aid in the charge sign determination for *W* detection. A detailed study is under way to determine the requirements for this upgrade. The detectors would provide a precise space-point measurement near the west endcap between the TPC and the endcap electromagnetic calorimeter as well as a precise point near the interaction point from the intermediate tracking detectors (section 3.3.3).

3.3.7 Micropattern TPC Readout (GEM)

One of the major developments required for operation at the highest luminosity of the upgraded collider is a replacement for the STAR TPC. The space-charge distortions and event pile-up will become unacceptable in the existing TPC at 40 times design luminosity in RHIC. An over-arching principle in the STAR upgrade plan is to maintain the STAR large coverage. Thus, a new central tracking detector is required which maintains the coverage and functionality of the present TPC but can operate at high luminosity. A very promising design has been developed which employs a compact TPC with a fast (high drift velocity) gas. A key element of the compact TPC is the proposed use of GEM technology for the readout planes. GEM (Gas Electron Multiplier) technology was invented by Fabio Sauli at CERN and has now been used successfully in the COMPASS experiment at CERN. The basic GEM structure is a 50μm thick copper clad Kapton foil with ~ 50-80 μm diameter holes in a hexagonal pattern with 100-140 μm pitch (see Figure 28). When a modest voltage is applied across the foil (a few hundred volts), a high field is produced in the holes which is sufficient to produce gas gain in a chamber gas.

With an appropriate field configuration (Figure 29), ionization produced by high energy particles passing through the gas can be efficiently collected into the holes, multiplied, and the multiplied electron cloud efficiently extracted from the other side of the foil. A single GEM foil can achieve a gas gain of over 10^3. With double or triple stacked foils, gains adequate for detecting minimum ionizing particles using standard chamber readout can easily be achieved while operating the foils at very conservative gains (a few x 10 each).

This technology holds great promise for a number of applications in STAR. When used in the readout plane for a TPC, the GEM foils have the advantage that the ion feedback from the gain region is small. This may allow a TPC to operate in STAR with no gating grid, *i.e.* continuously live. When coupled to an effective pipeline readout, this would offer tremendous flexibility in triggering. Since wire chambers are not required, one can avoid the massive frames required to support the wire tension. This is especially attractive for a compact inner tracker where other detectors may be placed outside.

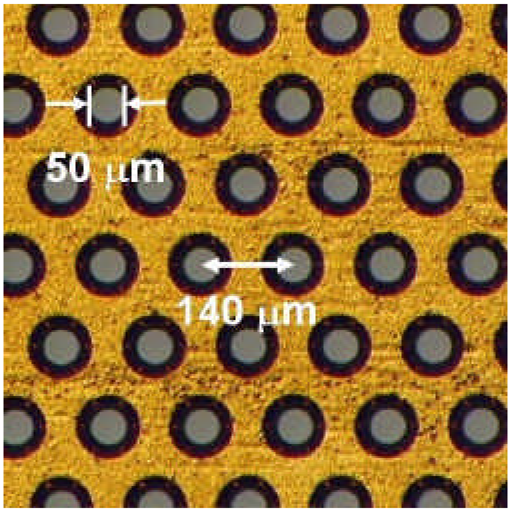

Figure 28. Photomicrograph of a GEM foil

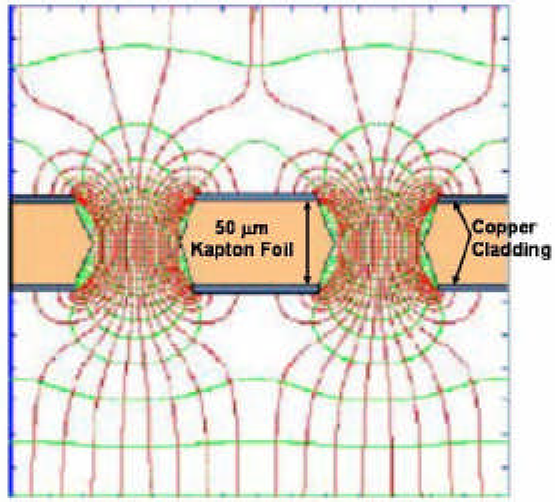

Figure 29. Cross section through a GEM foil showing field configuration for typical operation.

3.3.8 Magnet Upgrade

The STAR solenoid magnet presently has a maximum field of 0.5T. It has been suggested based on a preliminary study that the field could be increased by 50% or more without major work on the magnet itself. This could be accomplished by replacing the power supplies with higher current supplies and by increasing the cooling to the magnet. A more complete engineering study is required to assure that the magnet structure would sustain the increased forces. This increase in field would provide an increase in momentum resolution for high momentum tracks which will be quite valuable for the future physics program (jet and high p_T measurements). Since the work required is essentially all external to the STAR detector, and all involving conventional services, it could be carried out at any time once the engineering study is completed.

3.3.9 Instrumenting the Forward Region

Several interesting physics topics discussed in previous sections can be pursued with the addition of suitable detectors in the forward direction. These ideas are under active study in STAR, but have not yet been reviewed by the full collaboration.

3.3.9.1 Forward Hadron Calorimetry

The STAR detector is well instrumented in the pseudorapidity interval $|\eta| < 2$. For larger $|\eta|$, the forward time projection chamber (FTPC) provides tracking for multiplicity and charge sign determinations, but the solenoidal magnetic field of STAR does not provide significant momentum analysis of large-$|\eta|$ charged hadrons. Due to the hole in the STAR poletips, there is on average less than one radiation length of material between the interaction region and positions outside of the magnet at large pseudorapidity. These positions can be instrumented to allow charged hadron detection over a broader range of $|\eta|$ than is presently available, expanding possibilities for the STAR physics program. To date, electromagnetic (EM) calorimeters have been successfully operated outside of the STAR magnet and close to the beam pipe. These calorimeters have been used to study forward production of neutral pions in both d+Au and polarized proton collisions. Supplementing the forward EM calorimeters with hadronic calorimeters would allow an extension of the physics accomplished to date, and would allow for greater exploitation of the FTPC by triggering on leading high-energy charged hadrons or forward jets.

It would be natural to adapt the remaining modules of the calorimeter, originally constructed for AGS experiment 864, to provide forward hadronic calorimetry for STAR. The cost associated with new detector construction would be eliminated. Mechanical support and readout electronics are significant issues that would require modest capital investment and design work. Good jet containment could be supplied by a hadronic calorimeter that subtended $\Delta\eta \times \Delta\phi = 1.5 \times 1.5$. Positioned at an average distance of 7.5 m from the interaction a 12×12 array of the E864 calorimeter modules would be required to provide this coverage. The measurement of the Collins angle with transverse polarization would greatly benefit from symmetry of a forward jet detector left and right of one of the beams. Concurrent detection of events at $\pm\phi$ with both spin up and spin down beams would provide an important reduction in the systematic errors. For d+Au collisions, concurrent detection of forward jets at the same $|\eta|$ in the direction of both the deuteron and Au ions are also needed. Detailed simulations of the optimal size and arrangement of forward hadronic calorimetry for the physics outlined above must still be completed.

3.3.9.2 Roman Pots

With the addition of Roman Pots (RP) to the STAR detector, single and double diffractive pp interactions, in which one or both protons emerges intact from the collision can be studied. These interactions are characterized by rapidity gaps - regions of phase space containing no final state particles. In these collisions both interacting protons loose a small fraction of their initial energy, up to 5 - 10%. Combining data from the proposed Roman Pots with the information from the full STAR detector will allow the study of angular dependencies and correlations between the outgoing protons and the centrally produced system.

The precise location of the required detectors and kinematical coverage still need to be optimized. It will require detailed studies of the beam line optics and transport, as well as of the double Pomeron scattering kinematics. These studies are currently under way.

The first RP station will be located just in front of the DX magnet and will give access to large values of t (four-momentum transfer squared). It will detect scattered protons, which otherwise would not make it through the DX magnet acceptance, i.e. angles > 3 mrad. This RP station can also function as an independent luminosity monitor and multiplicity counter up to $\eta = 6$, etc. The following 1 or 2 stations will be located between the DX and the D0 magnets. One or two RP stations are also foreseen downstream of the D0 magnets for very small scattering angles (i.e. low $|t|$, down to 0.05 GeV^2 at $\sqrt{s}$ of 500 GeV).

The proposed RP will cover the whole azimuthal angle. This is different from conventional RP setups, which cover a limited azimuthal angle. Conventional silicon detectors will be used.(for instance up and down, or on one side of the beam). The RP will be of a hexagonal shape, divided into 6 sectors. Each sector will consists of a stack of 3 silicon detectors with X, U, and V views followed by a scintillator, which will function as a trigger. Conventional silicon detectors, with a pitch around 200 microns, will be used. The readout will be based on existing amplifier chips and sequencers, which can be easily integrated into STAR.

3.3.10 Future STAR Software and Computing Needs

The scientific program proposed in this decadal plan represents a daunting challenge for STAR software and computing. At present the STAR experiment records up to a PetaByte of data per year. The most statistics-challenged bulk physics measurements envisioned in the STAR decadal plan requires data sets an order of magnitude larger. It is not viable to use existing resources and conventional techniques to manage and analyze this magnitude of data. For example, while the search for rare triggers may be handled conventionally by a systematic scan of the entire dataset, it is clear that such approach would fail when facing a data sample composed of multiple million files and storage need exceeding availability. Specifically, data management and distribution, including distribution of second pass production physics summary files to remote institutions as well as first pass facility production, become problematic.

This presents a major challenge for the future RHIC program. Within STAR, a computing strategy based on Grid activities and the use of middle-ware tools is being explored as a mean to address STAR's future requirements. This effort is ongoing and activities are currently focused on putting in place the first elements of a production Grid infrastructure:

- With the help of Storage Resource Management (SRM) tools, for the past year over 20% of STAR data is reliably shipped between Brookhaven National Laboratory and Lawrence Berkeley National Laboratory.
- A job submission system developed as a wrapper around Grid middleware and traditional batch queuing systems has been developed. As a hybrid solution with its own job description language, this tool allows STAR to shield its users from the dynamic nature of the Grid while at the same time, provide a standard way to proceed with their analysis.

- Additionally, an analysis framework (or GridCollector) is being developed to allow the user to transparently fetch selected events from files distributed across the GRID rather than from a single large data set, thus resolving the “needle in a hay stack” problem.
- Other activities such as monitoring of the Grid fabric are easer underway or deployed on both major data sites (BNL and LBNL).

To complete the data management and data handling problem, STAR computing plans to develop, test and/or use replica registration service components, and will freeze of its fabric monitoring approach. In the coming year, work will begin on setting up a multi-site production environment using heterogeneous computing resources at minimum for Monte Carlo simulation. It is envisioned that initial use of the Grid for STAR analysis jobs will begin as early as 2004 at least at beta test level. The initial work that has been done forms the kernel of a developing infrastructure based on Grid which will be used to address the future software and computing requirements.

The ongoing STAR physics program, with ever increasing data throughput will continue to drive the need for the use of distributed resources available across all STAR collaborating institutions around the world. In the coming year we expect four collaborating STAR institutions to join the Grid development effort, providing manpower for controlled Monte-Carlo driven testing.

While production level data replication across the U.S. Grid has been, to date, successfully demonstrated, data production and data mining remain at an embryonic stage (developer level) and full user analysis is not currently possible due to the lack of several major components and the need for consolidation of the current framework. Much work remains to be done and in order to create the necessary software and computing environment required by the future STAR scientific program. It will be necessary to explore new approaches to sharing and competitiveness, and to seek partnerships both within and outside the field of nuclear physics. Long term planning and the development of a comprehensive Grid strategy are essential to the success of the STAR Decadal plan.

4 Summary

Beyond the initial discovery phase, beginning during the second half of this decade, the STAR research program will turn to a broader and deeper exploration of the fundamental properties of matter created by heating the QCD vacuum, the accompanying phase transitions, and the extremely hot, superdense states that precede the formation of a thermal plasma of quarks and gluons. These studies will address e.g., the nature of chiral symmetry breaking and how is it related to the masses of the hadrons; the relationship between the deconfinement and chiral transitions; the nature of a possible saturated gluon state in strongly interacting particles. The new matter produced at RHIC will provide a unique laboratory for a full, detailed exploration of the fundamental properties of QCD. Extensive studies of proton-nucleus and polarized proton collisions will contribute to a growing base of knowledge, providing essential information on the initial conditions, and the role of spin as a fundamental component of QCD.

The STAR detector program during the high luminosity era will center on precision measurements e.g., of the dynamics of heavy flavor (charm and beauty) production as a means of studying the various stages of formation and hadronization of QCD matter, the measurement of observables related to hard-scattering of partons in the kinematic range where perturbative QCD calculations can be reliably carried out, studies of electromagnetic probes (including direct photons) directly related to the formation and evolution of a deconfined state.

Additional studies will focus on the search for new phenomena in bulk QCD matter such as strong CP violation which is expected to be associated with the deconfinement phase transition. Such studies require very large samples of unbiased data ($>10^8$ events).

STAR will also continue a full program of spin physics measurements including the definitive measurement of the spin dependent gluon distribution of the protons $\Delta G(x)$ using direct photons, and first measurements of sea quark polarization ($\bar{u}$ and $\bar{d}$) using parity violating W decay. Additional measurements planned for the STAR spin program include studies of quark mass effects with b-quark jets, and probes of transversity via A_{TT} in quark-quark di-jets. This program requires an increase of RHIC luminosity for polarized protons by a factor of ~ 20 by 2006. A corresponding increase in polarization by a factor of ~ 2 is needed on the same time scale.

This program requires substantial upgrading of the detector to achieve the scientific goals of the STAR heavy ion program in the period up to 2010 ($4 \times$ the design luminosity, L_0) and during the era of high luminosity ($40 \times L_0$). Significant improvement in luminosity and polarization for polarized proton collisions, as well as significant detector upgrades are required to achieve the goals of the STAR scientiific program during this period. These upgrades include:

- a precision micro-vertex detector capable of directly observing charm and beauty decays;
- a fast, compact, high-resolution Time Projection Chamber;
- a full acceptance TOF barrel based on multi-gap resistive plate chamber technology

- a high rate data acquisition system and corresponding TPC front end electronics (FEE) upgrade to handle very large data volumes at high rates.
- a forward tracking upgrade to enable reliable charge-sign determination for W decay

Active consideration is also being given to instrumenting the forward STAR acceptance with hadron calorimetry and Roman Pots to extend STAR's scientific reach for spin physics and diffractive physics measurements.

To prepare for the second phase of STAR exploration, a plan has been developed which meets the science-driven requirements of the high luminosity STAR physics program. The plan calls for a robust program of detector and accelerator R&D beginning now. A series of incremental upgrades of the STAR detector's capabilities are to be accomplished between now and 2010, within the base program as much as possible, to allow STAR to take full advantage of ongoing incremental improvements in detector capability and the 4x RHIC luminosity era, while preparing for the 40x high luminosity running near the end of the decade

Appendix: Letter from Dr. Kirk

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February 28, 2003

Dr. Timothy Hallman, Spokesperson
STAR Collaboration
Physics Department
Brookhaven National Laboratory

Dear Tim:

The RHIC experimental program is now fully underway and the physics discoveries are emerging at a rapid and exciting pace. The relativistic heavy ion community, of which the collaborators of STAR are a central and key part, is currently reaping the benefits of a science planning and construction period that started in the 1980s when the RHIC ideas were first seriously pursued. In view of the decadal time scales that now characterize the evolution of 'big science' programs, it is not too early to expand our planning efforts for the next phases of the RHIC scientific program to include persons and communities not already participating. The recent Review of RHIC detector R&D proposals by an international panel of heavy ion and detector experts represents an important step in actualizing the planning that has occupied the RHIC experimental community since the start of the Nuclear Physics Long Range Plan activities in early 2001. We now seek to inform the wider nuclear physics community about the development plans for RHIC and its future physics program.

In this letter, I intend to focus primarily on the strategic time frame beyond the mining of accessible data regimes from our present facilities and detectors and their incremental improvements. Efforts to consider this longer-term planning regime have already been underway for some time in a number of venues as noted above, but this letter comes to solicit your participation in a specific planning exercise that will be of paramount importance for the U.S. Department of Energy and for the wider nuclear physics community. By this, I mean the clear identification of next generation science goals and the planning of facilities on the scale of the electron cooling luminosity upgrade of RHIC and its detectors, as well as eRHIC and possible large new detectors in the RHIC complex to realize these goals.

How does this objective link STAR and the management of BNL? I intend to involve the leadership of the present RHIC experimental collaborations, together with BNL's HENP Program Advisory Committee (PAC), in a joint consideration of the future ideas and options for evolution of the RHIC science program and facilities. Why choose this particular combination? I believe that the present RHIC collaborations have already engaged the best and brightest members of the heavy ion nuclear physics community and therefore represent the most natural starting point for consideration of future research paths for this field of science. I also believe that the BNL PAC represents a wise and experienced group of scientists who will provide insight and astute general criticism of the emerging plans of the RHIC community and how it can best realize these plans in a very competitive scientific marketplace.

To engage these partners in a productive dialog, the method that I plan to employ relies on the ability of the RHIC collaborations to produce concise documents that identify decade-scale science goals and facilities paths to reach these goals, together with the ability of the PAC to critique these goals and development paths from the perspective of the larger nuclear science community. At a later stage of this longer-term planning process, it is likely that workshops will be carried out to consolidate the goals and facility planning and members of the PAC will be encouraged to participate in these. For now, the PAC will act as reviewers and critics of the documents requested here.

So, to put this concept into action, I am asking you to organize within the STAR Collaboration, a group to produce a paper on the strategic physics goals of the collaboration as it evolves into the high luminosity phase of the RHIC program, a period that will be reached operationally not before about 2009 and will likely be complete only after 2010. For this exercise, you should address both the heavy ion and the polarized proton aspects of the contemplated program. Your plan should also describe the evolution of the STAR detector to meet the stated physics goals. The time period that is appropriate for this paper is the ten-year period from 2004-2013. Accompanying this letter is a short summary of how the luminosity of RHIC is anticipated to evolve that you may use as a time-frame guideline. You should also refer to planned STAR detector R&D as this work impacts your plans. At first glance, it may seem like a very early time to begin addressing the physics and detector issues that will dominate RHIC physics after 2009, but a purposeful examination of the strategic R&D and developmental time scales will confirm the need to begin planning now.

Because the Laboratory is also planning to develop a new collider capability, eRHIC, that will enable the field of virtual photon-hadron physics to be pursued at BNL, you are invited to address the physics goals and detector concepts for exploring this field as well. At the present time, we envision eRHIC as producing collisions only at the 12-o'clock interaction point while heavy ion collisions continue running simultaneously in the RHIC yellow and blue rings. We further envision that a new collaboration will form to exploit this new physics opportunity and that the new collaboration may attract some of its members from the existing RHIC experimental collaborations. I intend to provide an opportunity for such persons to begin discussing their ideas for eRHIC physics in this same time frame. The HENP PAC will consider the eRHIC ideas as well as the future RHIC program plans.

I should also note that the RHIC program from 2008 forward will face vigorous competition from the LHC heavy ion program. In addition to the ALICE detector collaboration, both the ATLAS and CMS detector collaborations are studying their respective capabilities for performing heavy ion experiments and are expected to participate in the LHC heavy ion program. The RHIC program for heavy ion collisions will need to be carefully planned to compete in this arena. There will be, on the other hand, interesting opportunities for productive collaborations on instrumentation with LHC groups that may be of value for STAR to explore in a cooperative RHIC-LHC R&D context. The polarized proton and eRHIC programs will face no direct competition but will still need to be generally compelling to continue to compete effectively for resources.

In addition to these strategic questions, there is one near-term issue that requires some careful thought on the part of STAR. This concerns the primary scientific goal that was identified for RHIC when it was approved for facility construction. This, of course, is the search for Quark Gluon Plasma. You and I, together with the other RHIC spokespersons, have already engaged in discussions of how to proceed in publicly *announcing* the QGP discovery (assuming we don't conclude that QGP is *not* created under RHIC conditions!), but we haven't yet engaged in discussion of what minimal and feasible set of measurements will provide strongly convincing evidence of QGP's existence. Accordingly, I ask you to provide the list of experimental measurements that STAR expects to achieve that bear on this question and a best guess as to the time frame for having such measurements in hand.

All this having been considered, let me now be more specific about the document that I am soliciting from STAR. The strategy paper should contain the following elements:

1. A list of the physics topics that the STAR collaboration expects to address in the period 2004-2013, with a short (paragraph length) statement of the anticipated physics impact of a successful measurements program. It is understood that unanticipated physics directions may emerge as the program evolves but there are prospective physics topics of significant interest that have already been identified and described. Please indicate a time and luminosity frame over which these topics are expected to evolve.
2. A brief outline of how the STAR detector is expected to evolve to meet the requirements of the prospective physics program. R&D necessary to meet the detector evolution should be noted and its time frame also incorporated in your plans.
3. A list of measurements that STAR expects to provide that bear on the question of the existence of QGP and when you expect that these measurements will become available.
4. A brief statement of how your collaboration is expected to evolve to carry out the projected plans. If you envision large changes in the composition or focus of the collaboration, please describe these and the reasons for them.

I would like the STAR paper to be completed and submitted to me no later than June 1, 2003. Upon receipt, I will provide it to the PAC members for their information and comments. By the time of the September 2003 PAC Meeting, the Laboratory will have formulated a plan for maximizing the scientific benefits of the submitted papers from all the contributing parties and will ask for PAC comments and recommendations on this plan. The Nuclear Physics Division of DOE will be kept abreast of these evolving strategic developments and their input incorporated.

A full set of strategic RHIC research direction papers have been solicited from each of the present RHIC collaborations and additional contributions in this area will also be solicited, through separate announcement posted to the RHIC Users website, from other interested parties in the nuclear physics community. The prospective eRHIC program and facility is one obvious example. As these strategic directions evolve, the related supporting arguments and detailed plans will be strengthened by appropriately targeted workshops and other developmental activities. These actions and activities will be announced later.

I have always believed that science is best carried out in a ‘bottoms-up’ manner and should be driven by practicing researchers. By adopting this approach of strategy papers from working collaborations, I hope to achieve both a comprehensive outreach and a researcher driven outcome. Your collaboration is expected to be a central player in this effort. I hope you will be able to respond effectively to this solicitation.

I am available to discuss the content of this letter as you may wish.

Best regards,

Thomas B.W. Kirk
Associate Laboratory Director
High Energy and Nuclear Physics

Cc: BNL HENP Program Advisory Committee Members
D. Kovar, DOE-NP

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